Research Programme of the Research Fund for Coal and Steel

FIre and Seismic performances of Hybrid fire WALLs in case of single-storey industrial and commercial steel buildings (FISHWALL)

Analysis of real fire development in typical single storey building

Nicolas Henneton – BRIAND

Jean-Baptiste Tramoni – CTICM

WP 1: Analysis of regulation requirements, fire and seismic actions applied to partition walls and design of tests

Deliverable: D1.2

Grant agreement No: 101034083

Version	Issue	Purpose	Author	Reviewer	Approved
A	D1.2	first version (09/02/2022)	J.B.Tramoni N. Henneton	ALL	C. Renaud
B	D1.2	revised version following comments from EC (13/10/2023)	J.B.Tramoni N. Henneton	ALL	C. Renaud

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ABSTRACT

It is well known that the intrinsic fire resistance of single-storey unprotected steel-framed buildings is largely sufficient to guarantee the evacuation of occupants in the event of fire. In consequence, for this type of building, the main concern of national fire regulations in Europe is how to prevent the spread of fire to the whole building. To achieve this objective, two performances shall be usually satisfied, namely, the appropriateness of constructive systems to ensure that there is no progressive collapse between fire compartments, and the efficiency of fire walls to stop the fire inside the initial compartment regardless of the state of structures exposed to fire. In practice, many constructional solutions can be implemented in order to preserve the integrity of the fire walls, while accepting that the fire exposed part of the structure may collapse. One of the most common solutions is to place a non-load bearing wall between two independent steel structures and to connect it to them by means of "fusible" links. In fire situation, these fusible links have to allow the wall to be disconnected from the structure affected by fire without endangering the separating function of the wall, which shall remain fixed to the steel structure on the other side of the wall and therefore not exposed to fire. However, due to the lack of corresponding scientific evidence, questions are being very often raised about the real efficiency of such systems in fire situation, which, in certain cases, have also to provide an adequate seismic resistance, if they are used in seismic areas.
Today, concrete or masonry wall solutions are frequently used for the compartmentation of buildings, predominately for low-rise commercial and industrial steel buildings. However, as an alternative, lightweight sandwich panels (comprising two thin flat metal faces and an insulated core) could become an appropriate steel fire wall solution, offering numerous benefits in comparison to other solutions, including fire resistance, durability, flexibility, easy dismounting and fast construction times. But, there is an evident lack of technical information about the adequate fire performance of such type of wall solutions when they are implemented in single-storey buildings with unprotected steel structure, which constitutes a major obstacle for their large use.
In this context, the overall goal of the FISWHALL project is to develop a design guidance and recommendations for an innovative hybrid fire wall solution based on lightweight steel-faced sandwich panels associated with unprotected steel structure under both fire and seismic actions, but considered individually. This will be achieved through the following specific tasks: i) Establishing of a full range of experimental evidence about the fire and seismic behaviour of the investigated hybrid fire wall solution by carrying out a number of tests; ii) Investigating intensively the fire and seismic performances of the above hybrid fire wall solution in combination with unprotected single-storey steel structures through a variety of parametric numerical studies by means of validated FE numerical models; iii) Developing both cost-effective and innovative "fusible" connection systems for fire walls to be used in combination with unprotected steel structures of single-storey buildings; and iv) Developing a design guidance and practical recommendations for the studied hybrid fire wall and fusible links solutions, on the basis of above studies, from which engineers can carry out very efficient design.

The present report aims at presenting in detail the fire simulations carried out using the computational fluid dynamics (CFD) model FDS to estimate the thermal actions to which the structure and the fusible systems associated to partition fire walls could be subjected in the event of a fire occurring in single-storey steel framed buildings. Several real fire scenarios leading to both localised and fully engulfed fires are chosen, referring to the reference buildings described in detail in the deliverable D1.1 [1] and taking into account the different occupancies of buildings targeted by the project, namely industrial, storage or commercial activities. Having briefly set out the main characteristics of investigated buildings, the selected real fire scenarios and the modelling assumptions, main results in the gas temperatures calculated inside investigated buildings are presented and briefly discussed.

1 INTRODUCTION

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In order to prevent the spread of fire inside buildings, fire safety regulations commonly require buildings to be divided into several zones of limited size and separated by means of partition fire walls. Among the possible wall solutions, the compartmentation of single-storey steel-framed buildings can be achieved by placing a non-load bearing wall between two independent steel structures and to connect it to them by means of "fusible" links. Even widely used in practice, to date such wall solution still very little available technical evidence showing their adequate real fire behaviour when used in single-storey building with unprotected steel structure. In fire situation, the fusible links have to allow the wall to be disconnected from the structure affected by fire without endangering the separating function of the wall, which shall remain fixed to the steel structure on the other side of the wall and therefore not exposed to fire. Unprotected steel-framed structures exposed to fire conditions usually exhibit two successive steps of structural behaviour. The first step is due to the thermal expansion of the heated members, which results in pushing forces on the neighbouring structures. Then, as steel increases in temperature, it loses its resistance and stiffness and the heated steel structure starts to fall inwards, leading to tensile forces on the neighbouring structures. In case of a fire wall between adjacent steel structures, a requirement is to ensure that this fire wall does not fail with the steel structure submitted to fire. Thus, fusible links must be designed to resist the pushing phase and to fail for the tensile phase. Furthermore, it is necessary to ensure that the fusible systems located on the fire exposed side will fail before those located on the other side under the tensile forces induced by the collapse of the heated part of the steel structure

In this context, this report presents in detail the fire simulations carried out using the FDS model to estimate the thermal actions to which the structure and the fusible systems associated to partition fire walls could be subjected in the event of a fire occurring in single-storey steel framed buildings. FDS is a Computational Fluid Dynamics (CFD) model which is widely used in fire safety engineering to simulate in a realistic way the fire development and propagation in buildings. Several real fire scenarios are defined, referring to the reference buildings described in detail in the deliverable D1.1 [1] and taking into account the different occupancies of buildings targeted by the project, namely industrial, storage or commercial activities. Fire scenarios are selected to lead to localised or fully engulfed fires. Having briefly set out the main characteristics of investigated buildings, the selected real fire scenarios and the modelling assumptions, main results in the gas temperatures calculated inside investigated building cases are presented and briefly discussed.

The adequate structural behaviour of the investigated fusible link solutions under real fire conditions will be assessed later in WP3, especially from global 3D modelling intended to be developed in the scope of the task 3.6 to investigate the mechanical response of steel structures associated with fire walls using "fusible" links.

2 DESCRIPTION AND CARACTERISTICS OF SELECTED BUILDINGS

2.1 Building description

The single-storey buildings considered in this report correspond to the reference steel-framed buildings described in detail in the deliverable D1.1 of the project FISHWALL [1]. It is assumed here that buildings are not subdivided and enclose only one fire compartment occupying the total ground area: namely 1400 m², 3100 m², 6000 m² and 12000 m² respectively. It can be noted that such sizes of fire compartment can be usually classified from small to very large. The main dimensions of investigated buildings are summarised in Table 1. More detailed information can be found in deliverable D1.1. It should be noted that chosen configurations are case studies. Provisions were taken into account in accordance with regulations applicable to each country.

For each building, external walls are made up of common double skin cladding with insulation while the roofs consist of common steel sheeting with insulation. Buildings are equipped with several automatic smoke vents and skylights, with a total area of 9% of floor areas, according to the considered building. The location and sizes of smoke vents and skylights is specified later in the report.

Table 1: Main dimensions of selected buildings

Building	Width (m)	Length (m)	Maximum height (m)	Floor area (m²)
1	30.0	46.3	6.3	1400
2	51.0	61.0	10.1	3100
3	60.0	100.0	11.2	6000
4	89.0	134.0	13.0	12000

The following figures give a plan view of each selected reference building.

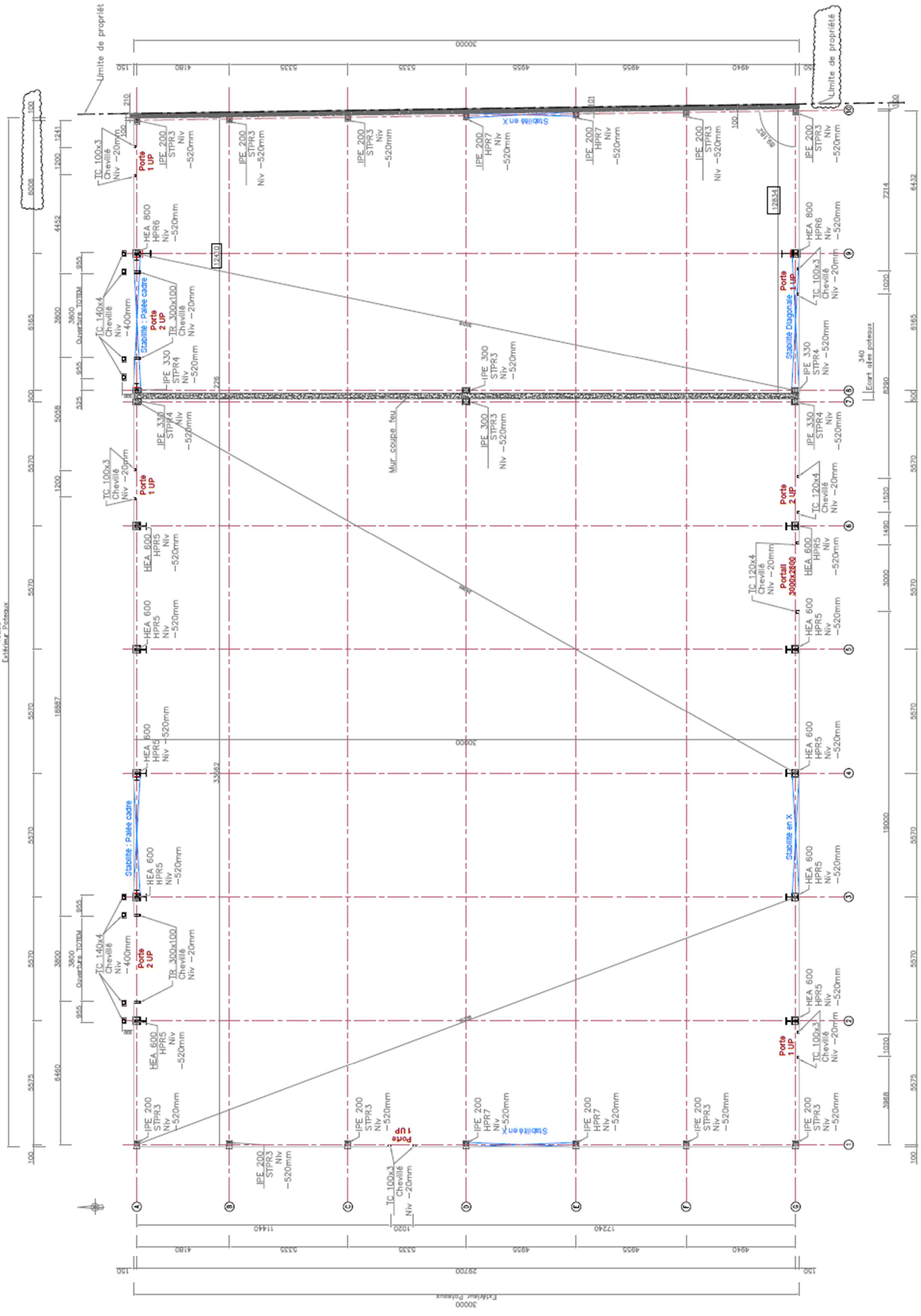


Figure 1: Plan view of building n°1 [1]

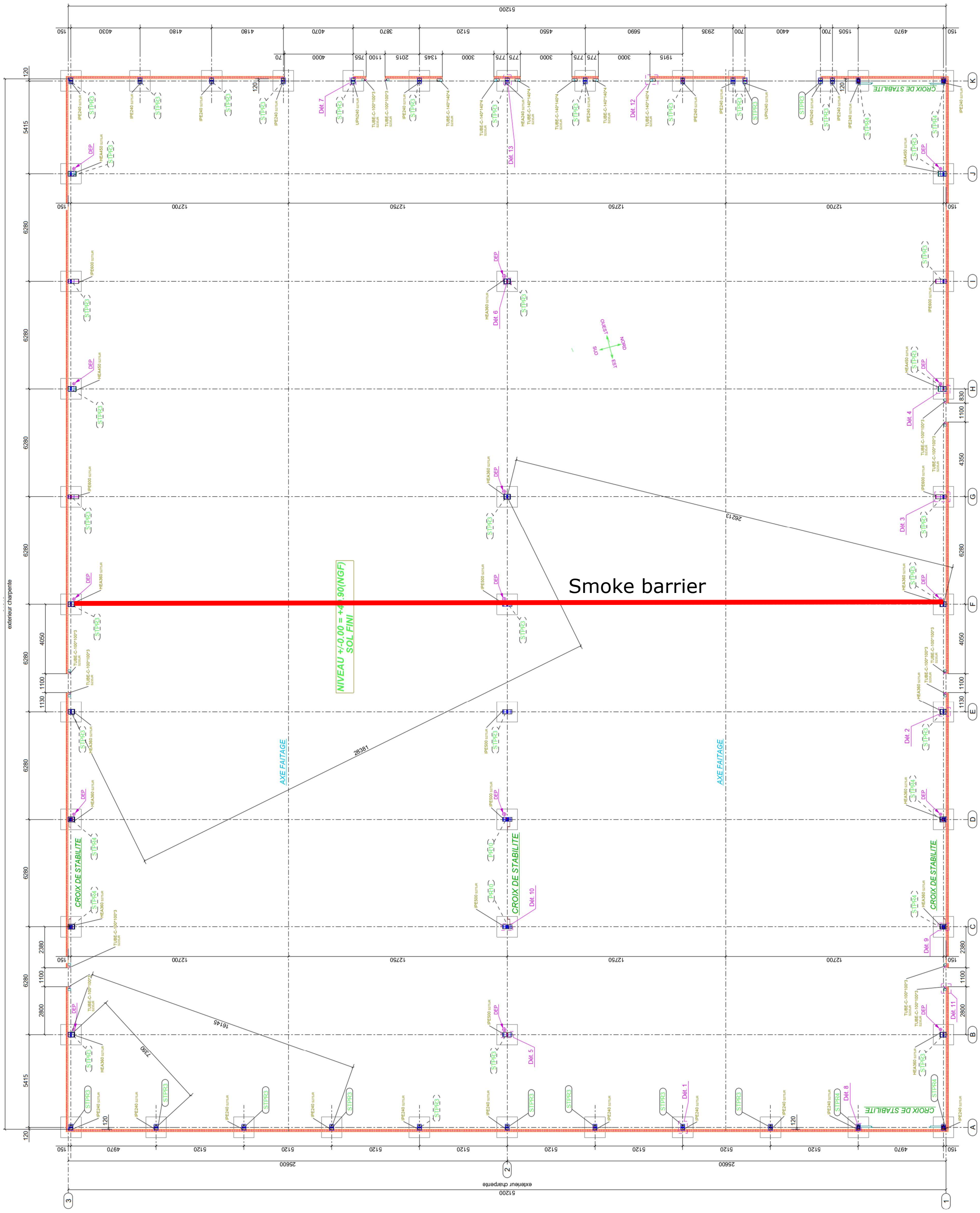


Figure 2: Plan view of building n°2 [1]

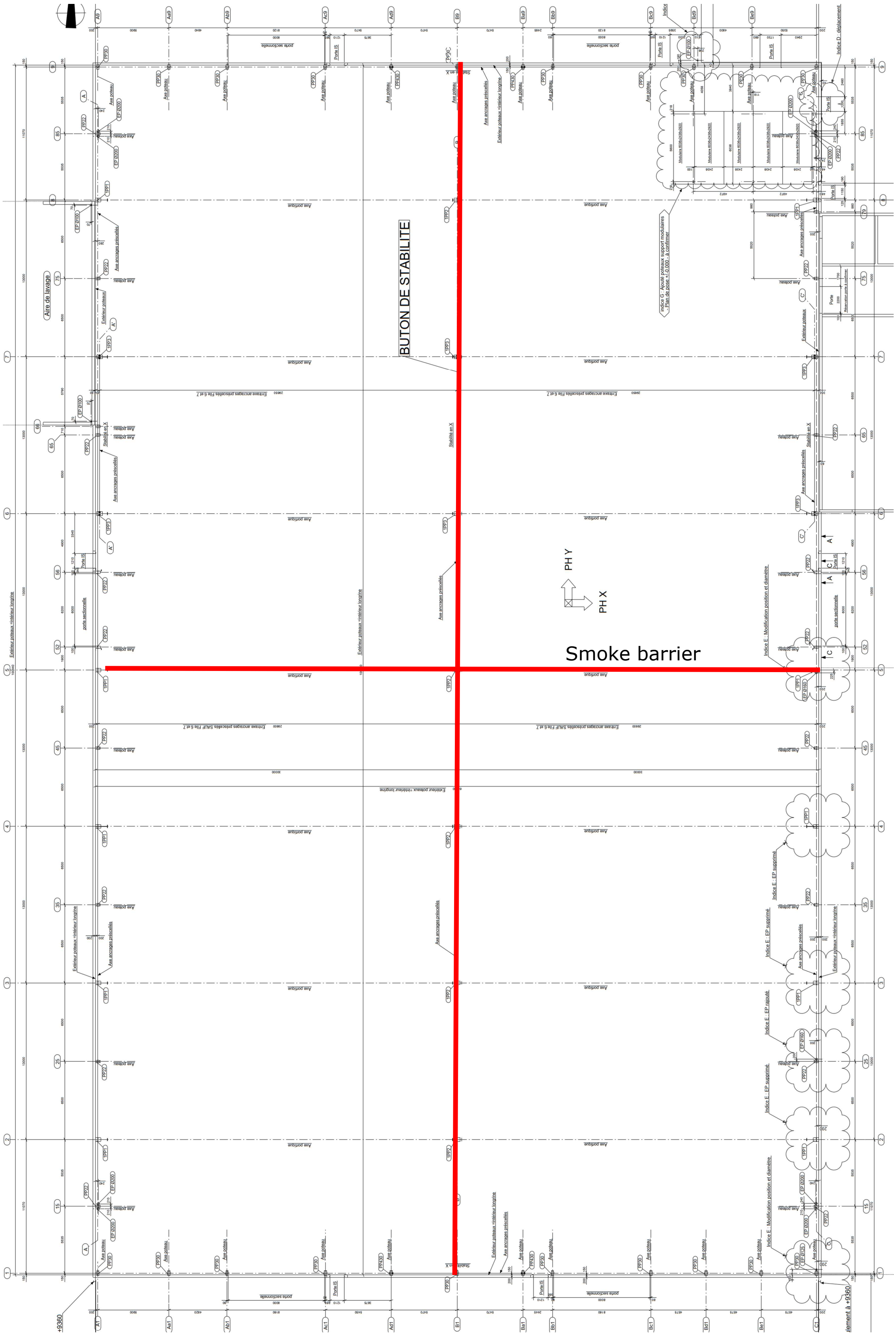


Figure 3: Plan view of building n°3 [1]

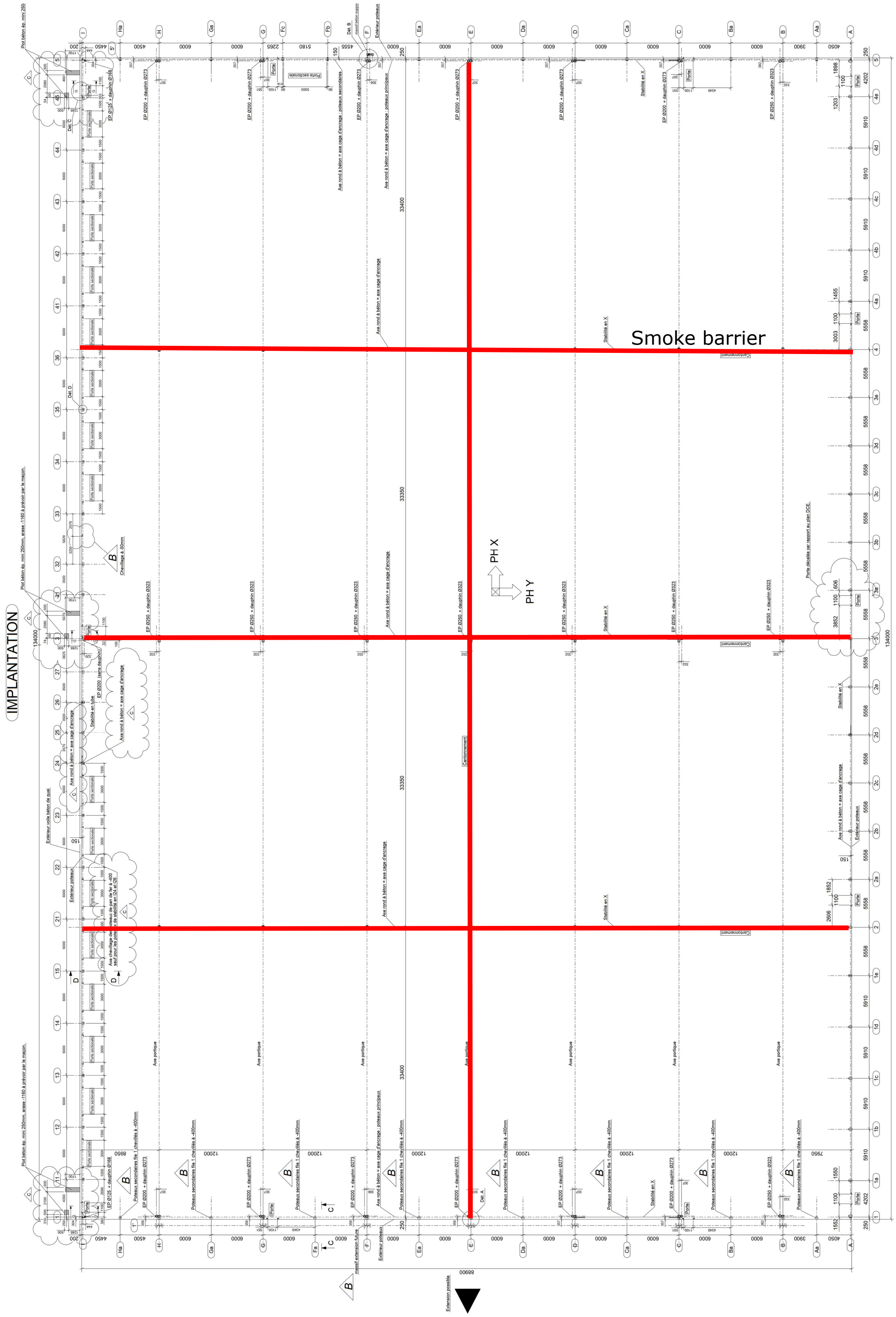


Figure 4: Plan view of building n°4 [1]

2.2 Building activities

Building activities are chosen to cover all representative occupancies of single-storey buildings targeted in the scope of the project. Thus, three building types associated to distinctive interior arrangements related to the considered activity are studied:

- Warehouse with palletized storage racking systems,
- Supermarket with shelf storage systems, and
- Industrial building enclosing bulk storages.

2.2.1 Warehouses

In warehouses, goods are usually stored using palletised racking systems and bulk storage areas. In the present section, only the storage racking system is considered, as illustrated in Figure 5. Configurations with bulk storage areas are studied in the section 2.2.3 related industrial building.

Generally, common racking systems consist of an assembly of multiple row racks separated with wide aisles to allow an easy loading and picking of stored pallets. Racking systems usually combine single row racks or double row racks, the latter consisting the most often of two single row racks placed back to back. They are arranged typically with single row racks on either sides of the racking systems and double row racks down the middle of buildings. It can be noted that the type of forklifts or handling equipment used, the type of goods and the height of the warehouse determine the width of the working aisles and the level number and height of the racks.

Adopting common rack sizes, the arrangement of the racking systems chosen in the study is updated according to the size of the considered building. It was decided by the project team to investigate four cases of warehouses:

- Building n°1: The racking systems consist of four double row racks and two single row racks with 3.2m wide aisles, each 34.4 m long approximately (see Figure 6). All racks have a total height of 5.6m and three loading levels, each 1.9m high approximately. Row racks are parallel to the longer sides of the building;
- Building n°2: The racking systems consist of nine double row racks and two single row racks, each 39,2m long approximately (see Figure 7). All racks have a total height of 7.6m and four loading levels, each 1.9m high approximately. Row racks are perpendicular to the longer sides of the building;
- Building n°3: The racking systems consist of nine double row racks and two single row racks, each 88m long approximately (see Figure 8). All racks have a total height of 7.6m and four loading levels, each 1.9m high approximately. Row racks are parallel to the longer sides of the building;
- Building n°4: The racking systems consist of fourteen double row racks and two single row racks, each 118.8 m long approximately (see Figure 9). All racks have a total height of 7.6m and four loading levels, each 1.9m high approximately. Row racks are parallel to the longer sides of the building;

In all cases, it is considered that single row and double row racks are 1.2 and 2.8 m wide, respectively. A picking zone is also present on 10 m.

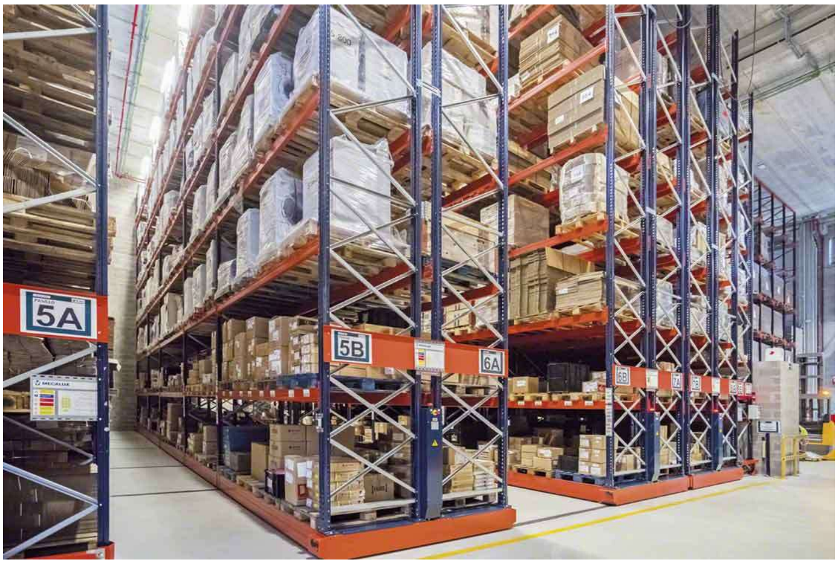


Figure 5: Example of palletised racking systems in warehouses (source: www.Mecalus.Com)

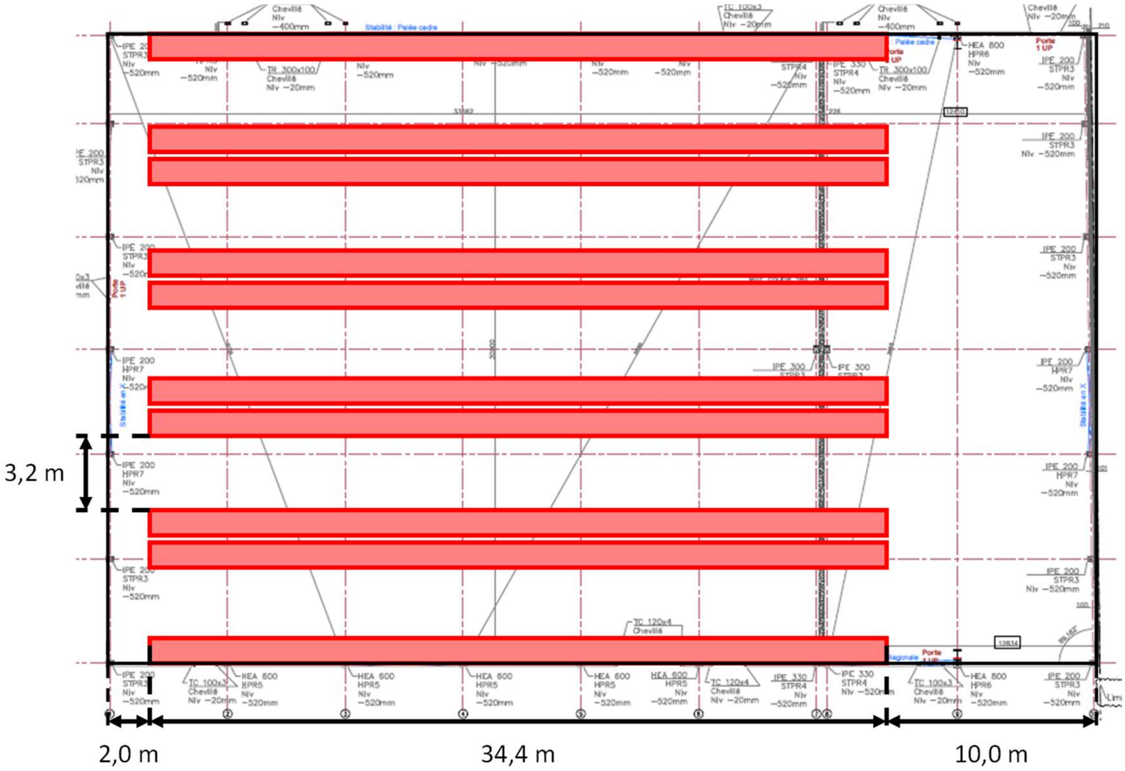


Figure 6: Racking area defined in building n°1

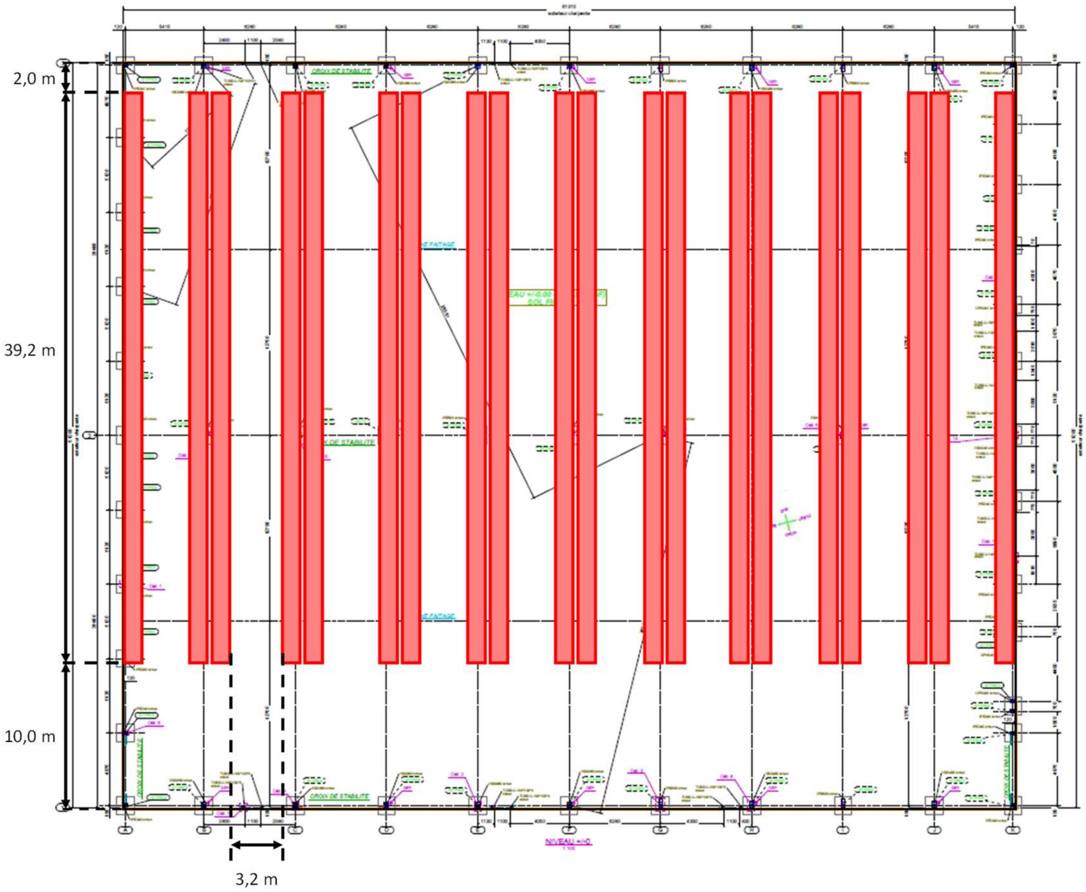


Figure 7: Racking area defined in building n°2

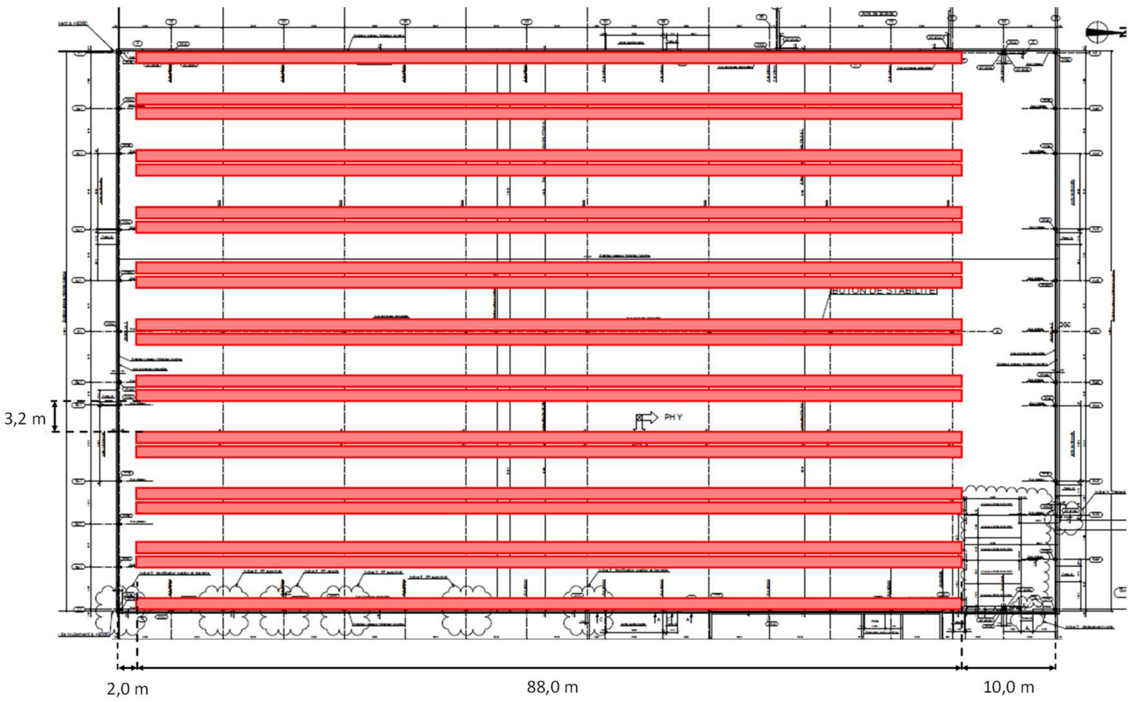


Figure 8: Racking area defined in building n°3

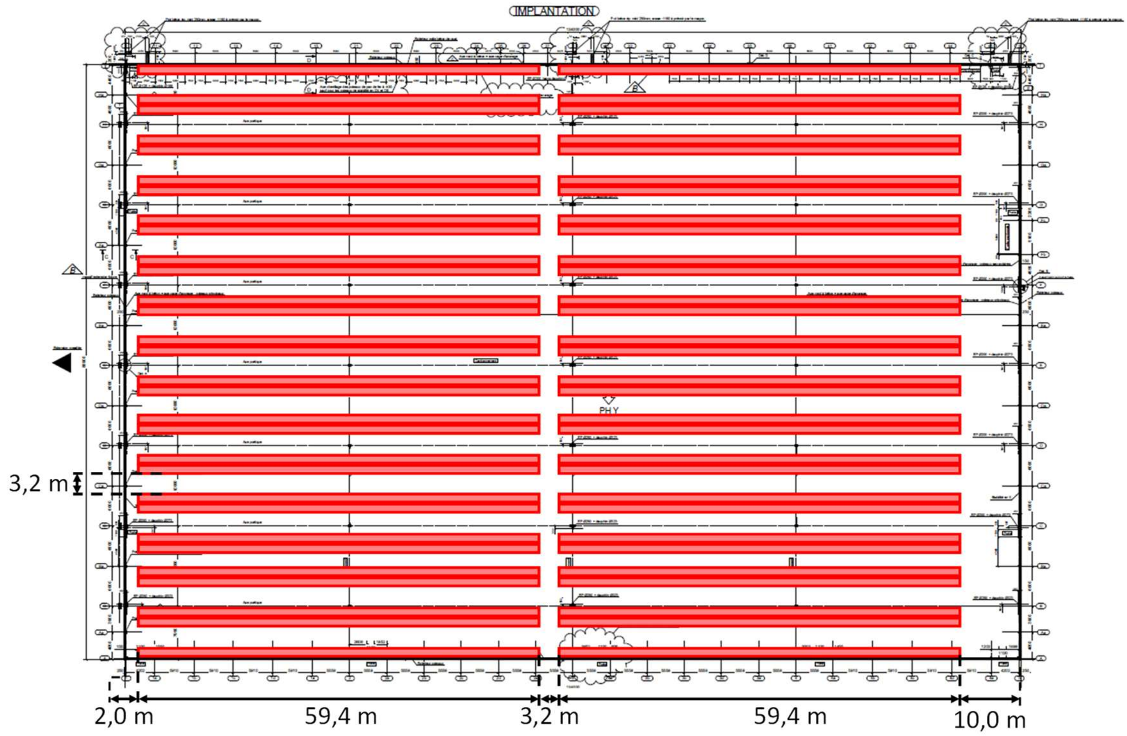


Figure 9: Racking area in building n°4

2.2.2 Supermarkets

In supermarkets, various types of products can be encountered (clothing, toys, cosmetics, cleaning products, etc.). They are usually stored using stacking shelves, separated by wide enough alleys to permit the passage of customers and trolleys (as illustrated in Figure 10). The height of stacking shelves is usually limited to permit the customers to easily access to the stored goods.

Figure 10: Examples of hypermarkets with stacking shelves
(source: CTICM from on-site visits of real commercial buildings)

Adopting common shelf sizes, the arrangement of the shelf storage systems chosen for the study is updated according to the size of the considered building. It was decided by the project team to investigate two cases of supermarkets:

- Building n°1: The shelf storage systems consist of eighteen double row shelves and two single row shelves with 1.8m wide alleys, each 20.0 m long approximately (see Figure 11). Row racks are perpendicular to the longer sides of the building;
- Building n°2: The shelf storage systems consist of twenty-four double row shelves and two single row shelves with 1.8m wide alleys, each 38.8 m long approximately (see Figure 12). Row racks are perpendicular to the longer sides of the building;

In all cases, it is considered that single row and double row shelves are 0.4 and 0.8 m wide, respectively. All shelves have a total height of 2m and three storage levels, each 0.8m high approximately.

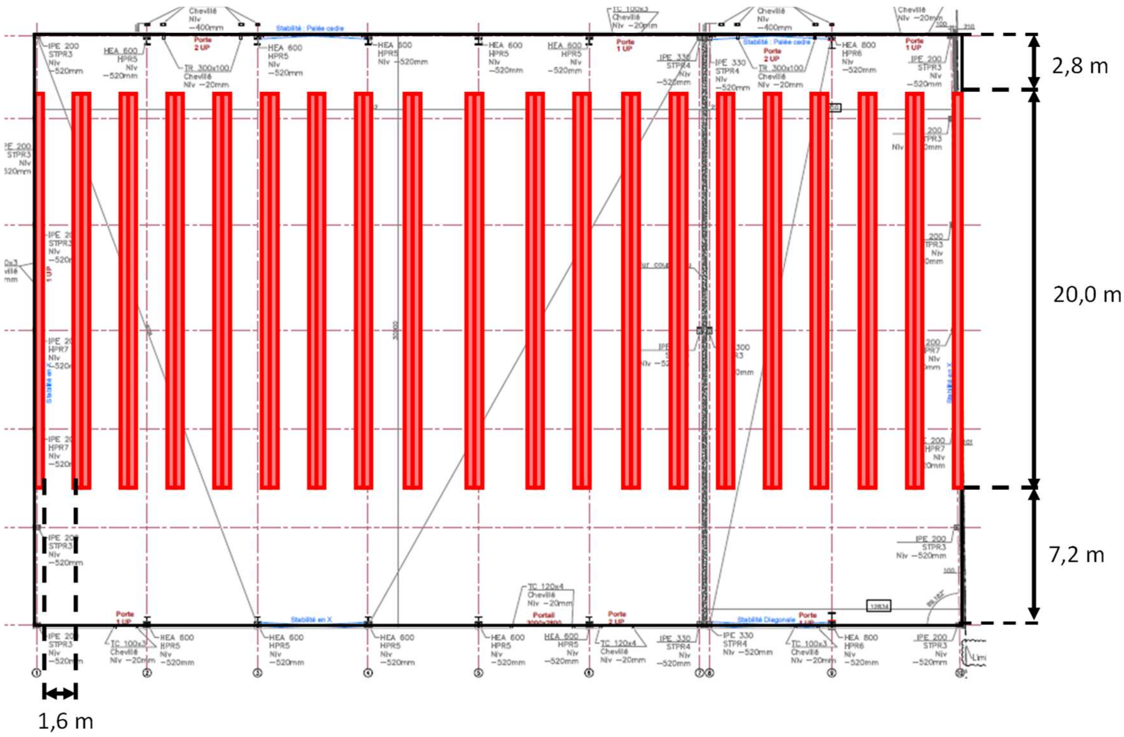


Figure 11: Shelf storage area defined in building n°1

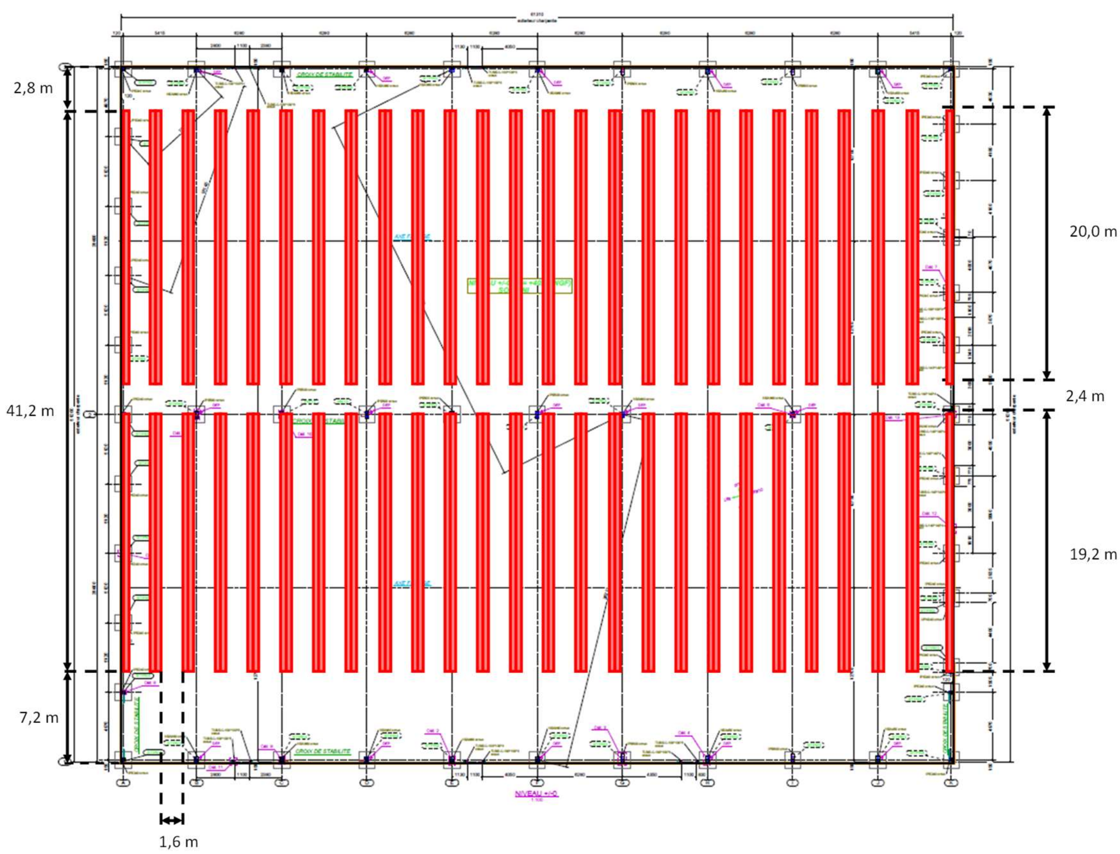


Figure 12: Shelf storage area defined in building n°2

2.2.3 Industrial buildings

In industrial buildings, usually the fire load is non-uniformely distributed. In addition to manufacturing lines or any other industrial processes, generally it can be found several storage areas of limited sizes, like bulk storages, with a large amount of combustible materials either at the beginning of the process (raw materials) or at its end (finished goods before storage in another building). An example of bulk storage is presented in Figure 13.

Figure 13: Bulk storage example (source: CTICM from a on-site visit of a real industrial building)

Since the bulk storages can have a significant effect on the fire development in industrial buildings, they are the only considered here. Indeed, production lines are mainly constituted of equipment with a large amount of incombustible materials such as steel. The arrangement of bulk storages chosen for the study is updated according to the size of considered buildings. It was decided by the project team to investigate two cases of industrial buildings:

- Building n°1: three bulk storage locations near or far away from compartment walls are considered as illustrated in Figure 14;
- Building n°2: three bulk storage locations near or far away from compartment walls are considered as illustrated in Figure 15;

With these locations, the fire will have a direct impact on close steel members while elements further away will be less impacted.

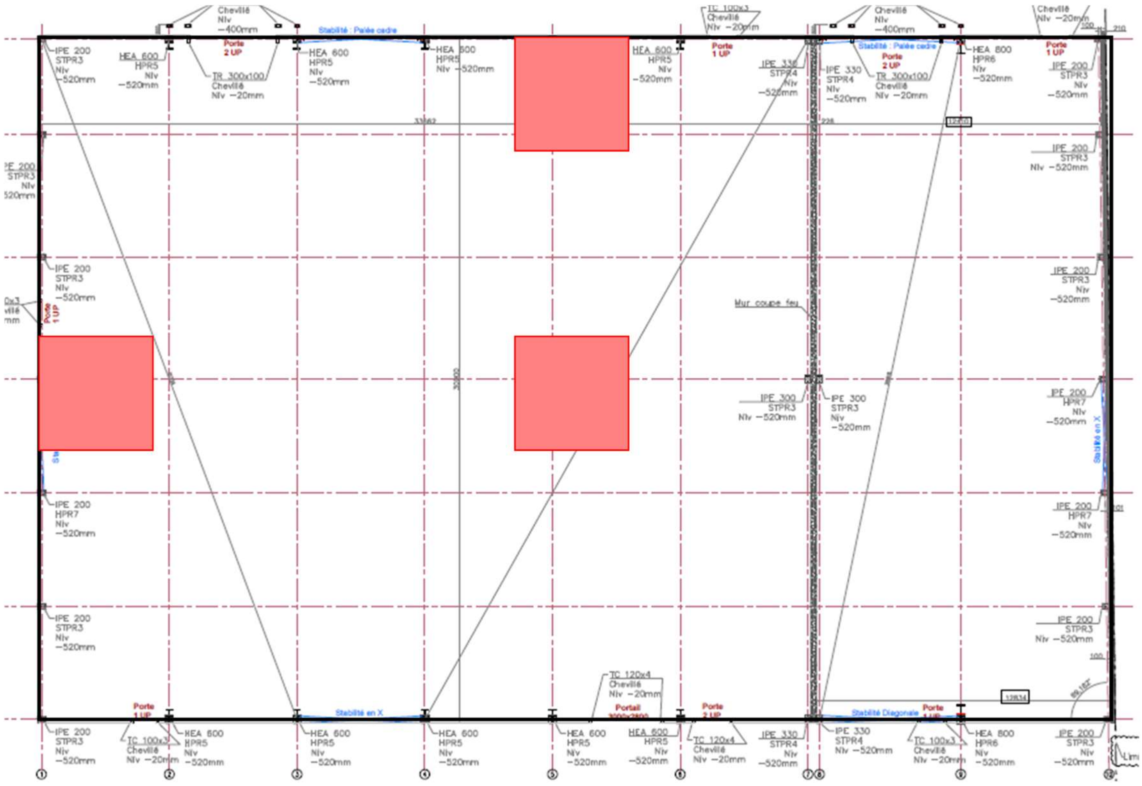


Figure 14: Bulk storage area defined in the building n°1

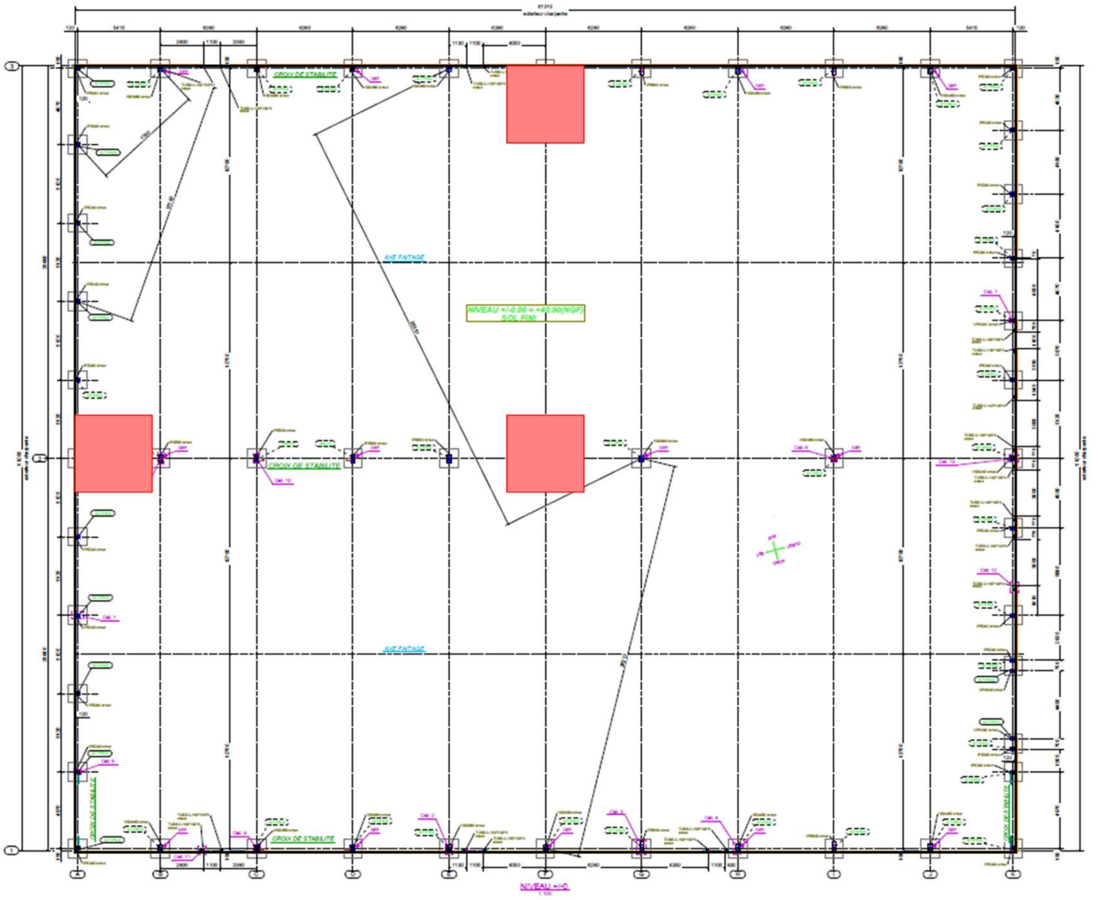


Figure 15: Bulk storage area defined in the building n°2

2.3 Fire safety related devices

Usually, fire regulations require that fire compartments are subdivided into "smoke zones" of limited size and equipped with a smoke extraction system.

According to their sizes, the considered buildings are subdivided into several "smoke zones" bordered by 1m high smoke barriers, considering a maximum area of 1 500m² approximately. The subdivision of buildings is indicated in Figure 1 to Figure 4.

The smoke extraction in each building is carried out in a natural way, using smoke vents. In addition, the presence of skylights is common to provide daylight inside buildings. However, skylights rarely withstand temperatures encountered during fire. Thus, their melting contributes to the smoke control.

The locations of smoke vents and skylights are shown in Figure 16 to Figure 19. For each building, the proportions of smoke exhaust area are as follows:

- Building n°1: 12 smoke vents and 12 skylights are present on the roof. Their respective surfaces correspond to 2.2% and 7.2% of the floor area ;
- Building n°2: 16 smoke vents and 16 skylights are present on the roof. Their respective surfaces correspond to 2.1% and 7.0% of the floor area;
- Building n°3: 32 smoke vents and 32 skylights are present on the roof. Their respective surfaces correspond to 2.1% and 7.2% of the floor area;
- Building n°4: 64 smoke vents and 64 skylights are present on the roof. Their respective surfaces correspond to 2.1% and 7.3% of the floor area;

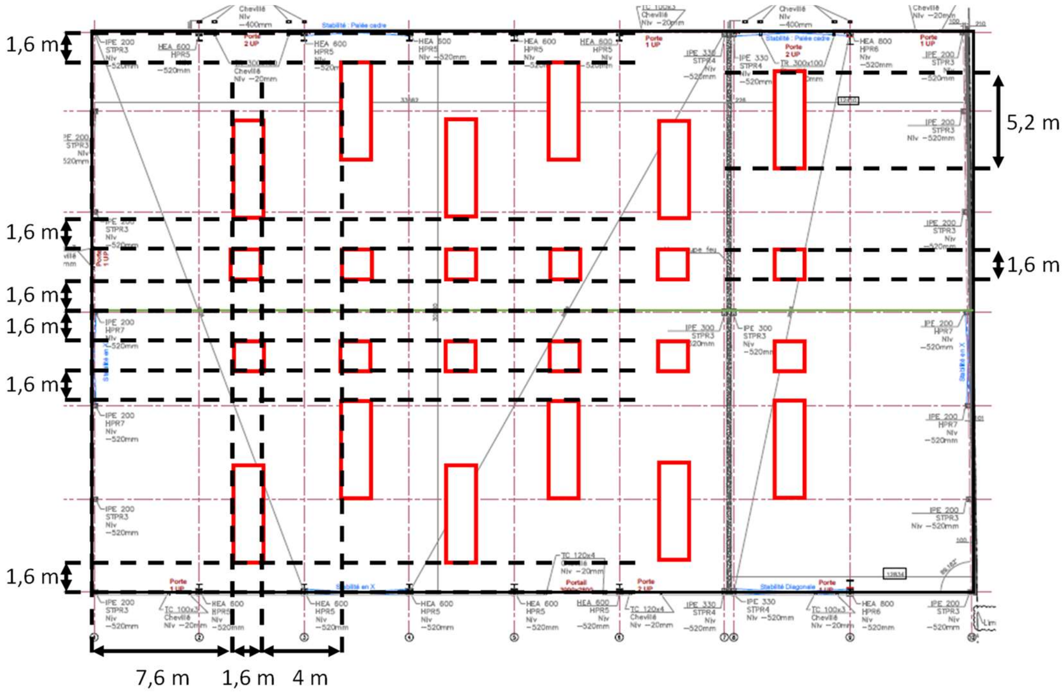


Figure 16: Smoke vents and skylights locations in the building n°1

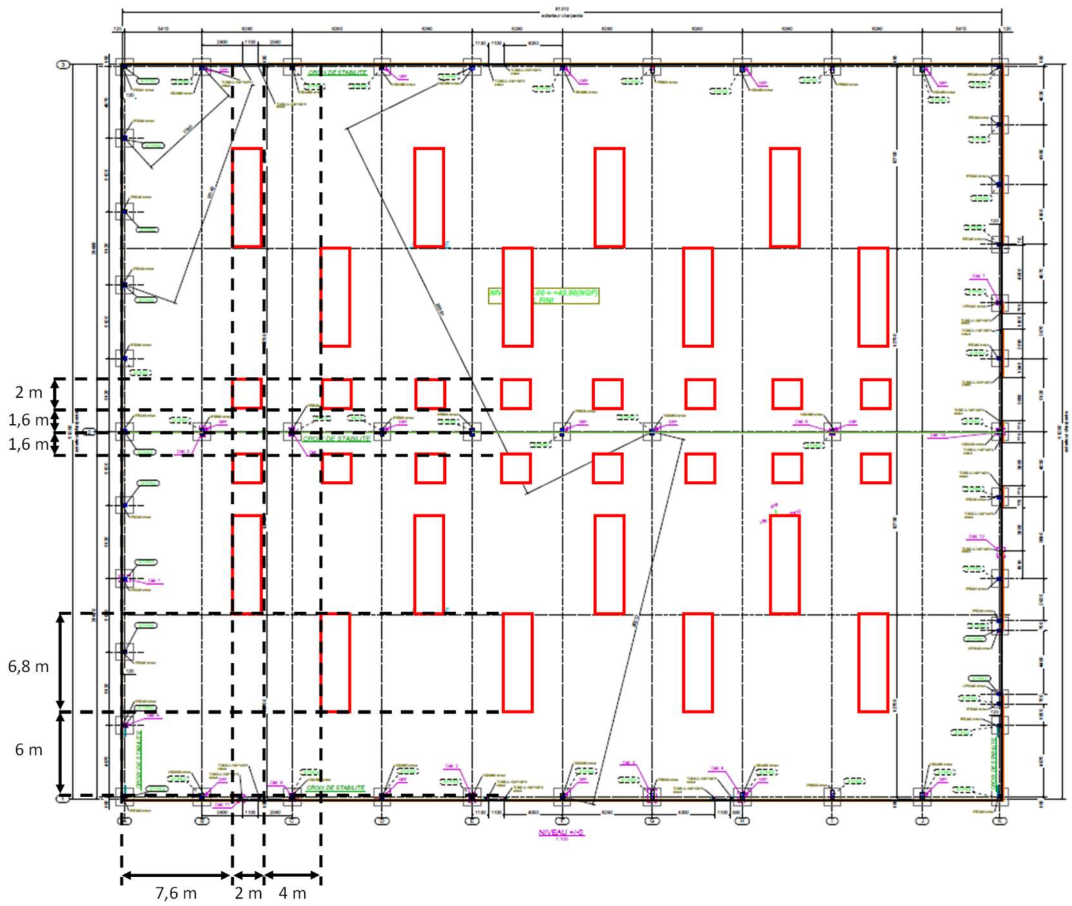


Figure 17: Smoke vents and skylights locations in the building n°2

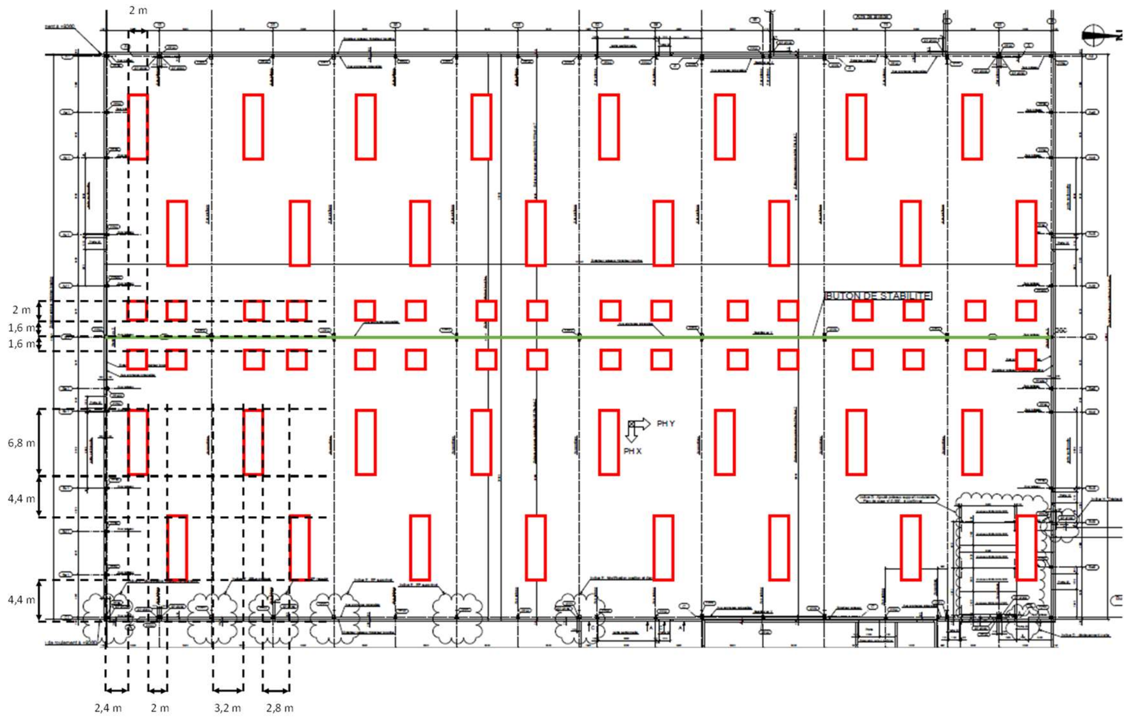


Figure 18: Smoke vents and skylights locations in the building n°3

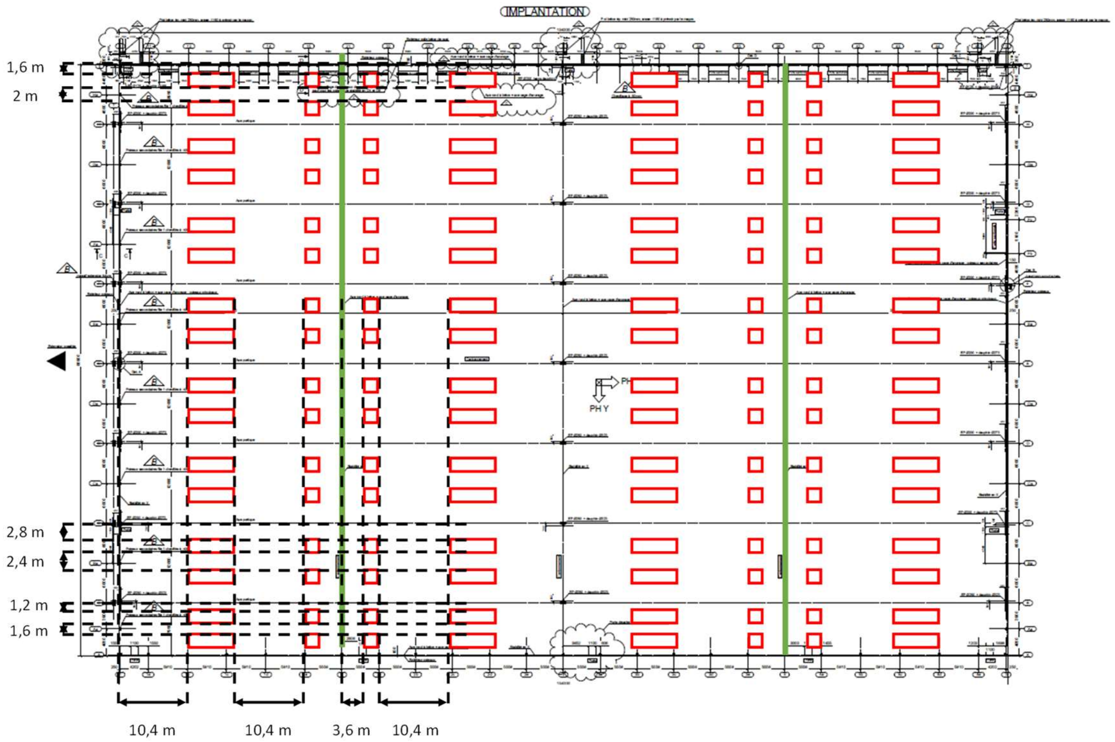


Figure 19: Smoke vents and skylights locations in the building n°4

3 POSSIBLE FIRE SCENARIOS

3.1 Design fire scenarios

A design fire scenario is a qualitative description of the course of a particular fire with respect to time and space. It involves a description of fire initiation, the growth of fire on the first item ignited, the spread of fire, the interaction of the fire with its environment and its decay and extinction [2].

Fires can occur in almost any location of a building. It is therefore impossible to consider every fire which may occur in the building, and the case realistic design fire scenario has to be selected. The factors considered in order to select the more challenging design fire scenarios concern:

- The fire itself (distribution and type of combustible materials, fire load density, fire spread),
- The factors influencing the fire development (ventilation conditions, state of doors, fire compartment size, etc.), and
- The structural engineering factors such as the position of the fire relative to bracing systems, columns, or other loaded members.

Fires are usually split into two different types, namely localised fires (fires concerning combustible materials in a localised area) and compartment fires or fully developed fires (fires in a compartment with all surfaces of combustible material burning). The transition between the two stages is the flashover. It may occur that the compartment is too large or too high for a flashover to develop and so the fire remains a localised fire, which is moving throughout the whole compartment (traveling fire), with different areas engulfed at different times, depending on how much fire load is available and how fast the fire load is consumed. Such a fire could be a critical design case for a structure, as the heating and cooling of the structural elements occur at times relatively close to each other.

3.2 Design fires

Once the design fire scenarios are selected, the characteristics of design fires have to be determined. A design fire is a simplified but still representative description of the complex physical and chemical processes occurring in a fire. Design fires are usually characterized from a heat release rate (HRR) curve, i.e. the evolution of the heat released by the fire as a function of time. The HRR must be simplified, but representative of the main physical and chemical phenomena involved in the fire. The fire is usually characterized by 3 successive phases:

- A growing phase;
- A fully developed phase;
- Then, a decay phase until extinction.

The growing phase corresponds to the period from the fire ignition on the first fuel up to the propagation to the full quantity of fuel present in the compartment. The full developed phase is characterized by a substantially steady burning rate, as it can occur in ventilation or fuel controlled fires. Finally, the fire intensity decrease until its full extinction during the decay phase.

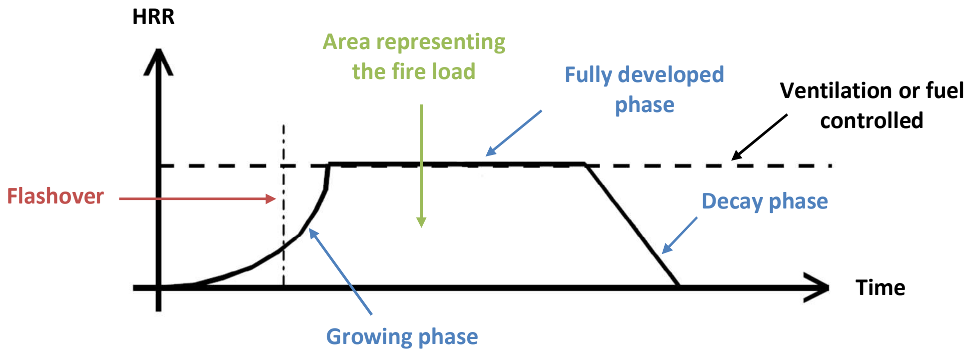


Figure 20: Example of fire design and associated phases

Fire tends to reach a fully developed phase. However, two situations can occur depending on the ratio between the quantity of combustible materials available and the oxygen income. If the quantity of combustible materials involved in the combustion is too important in regards to the incoming air, the HRR is limited by the ventilation. Conversely, if the quantity of incoming air is enough, the full HRR corresponds to the one released by the whole quantity of the combustible materials.

There are three approaches to determine the Heat Release Rate (HRR) as a function time:

- Analysis of the experimental data available in the literature;
- Construction of each part of the curve (growing, stationary and decay phases) by using analytical rules and parameters depending on the type of building, such as the commonly used relationships given in EN1991-1-2 [3];
- Use of fire modelling to assess the HRR in function of time.

The approaches based on the EN1991-1-2 and modelling are briefly presented in the following sections.

3.2.1 HRR curve determined from Eurocode 1 part 1-2 (EN1991-1-2)

According to EN1991-1-2, the fire load must be determined as a first step. It corresponds to the total heat that can be released by the entire quantity of combustible materials present in the compartment. It could be determined by listing the amount of combustible materials and using net calorific values of the combustibles involved. It may be also be defined in a statistical way.

The EN1991-1-2 gives a table of fire load densities according to the building occupancy, which should be related to the floor area (see Table 2).

Table 2: Fire load densities [MJ/m²] for different occupancies [3]

Occupancy	Average	80 % Fractile
Dwelling	780	948
Hospital (room)	230	280
Hotel (room)	310	377
Library	1500	1824
Office	420	511
Classroom of a school	285	347
Shopping centre	600	730
Theatre (cinema)	300	365
Transport (public space)	100	122

Then, the growing phase is given by the following expression:

$$\boldsymbol{Q} = \boldsymbol{10^6} \left(\frac{\boldsymbol{t}}{\boldsymbol{t_\alpha}}\right)^{\boldsymbol{2}} \quad \text{[MW]}$$

where $\boldsymbol{Q}$ is the heat release rate in [W], $\boldsymbol{t}$ is the time in [s] and $\boldsymbol{t_\alpha}$ is the time needed to reach a heat release rate of 1 MW.

The parameter $\boldsymbol{t_\alpha}$ and the maximum heat release rate $\boldsymbol{HRR_f}$, for different occupancies, are given in the following table.

Table 3: Fire growth rate and HRR_f for different occupancies [3]

Occupancy	Fire growth rate	t_α [s]	HRR_f [kW/m²]
Dwelling	Medium	300	250
Hospital (room)	Medium	300	250
Hotel (room)	Medium	300	250
Library	Fast	150	500
Office	Medium	300	250
Classroom of a school	Medium	300	250
Shopping centre	Fast	150	250
Theatre (cinema)	Fast	150	500
Transport (public space)	Slow	600	250

The fire growth is then limited, either by the oxygen income or the quantity of combustible materials. The theoretical maximum HRR, assuming non oxygen limitation, is given by the following formula:

$Q_{max} = HRR_f \times A_{fl}$ [MW]

where A_{fl} can be easily defined by the layout of the combustible materials of the fire compartment area.

If the oxygen supply is not enough, Q_{max} is defined by the geometric parameters of the openings. The expression then become:

$Q_{max} = 0{,}10 \times m \times \Delta H_C \times A_v \times h_{eq}$ [MW]

where A_v is the opening area [m^2], h_{eq} is the mean height of the openings [m], ΔH_C is the net calorific value of wood (17,5 MJ/kg) and m is the combustion factor (0,8).

Finally, the decay phase is assumed to start when 70% of the total combustible materials load is consumed. This phase may be assumed to be a linear decrease starting when 70 % of the fire load has been burnt and completed when the fire load has been completely burnt.

3.2.2 Predicting the HRR curve by CFD simulations

CFD models are models that divide the fluid domain under study into a large number of control volumes or "meshes" at which the quantities are assumed to be uniform. Each mesh is assigned unknowns representing the values of the physical quantities of interest. It is then a question of solving numerically, in a local and unsteady manner, equations translating the laws of exchange and conservation of mass, quantity of movement, species and energy.

Meshes are cubic so all volumes must be defined as parallelepipeds. Thus, complex geometries must be simplified and it is needed to keep the assumptions as simple as possible. However, it is easy to represent simple geometries as pallets.

The combustible materials is typically modelled as a rectangular solid, which can release heat from all its surfaces. However, a large number of parameters must be filled in to represent combustion as accurately as possible:

- Amount of combustible material and its characteristic thickness [m];
- Heat Release Rate Per Unit Area (HRRPUA [kW/m^2]);
- Heat of combustion (or net calorific value, $\boldsymbol{\Delta H_C}$ [MJ/kg]);
- Density $\boldsymbol{\rho}$ [kg/m^3];
- Specific heat $\boldsymbol{C_p}$ [J.K^{-1}kg^{-1}];
- Thermal conductivity $\boldsymbol{\lambda}$ [W.K^{-1}m^{-1}];
- Ignition temperature $\boldsymbol{T_{ig}}$ [°C];

In such 3D models, the fire growth and HRR in function of time can be modelled from a flame spreading along a combustible surface involved in the fire:

- Except for the first pallets to ignite, a temperature of ignition is associated to the combustible materials. When a part of its surface reaches the ignition temperature, this part starts producing heat as defined by the user. Indeed, the heat release rate per unit area depends on the heat exposure: the greater the heat exposure, the faster materials reach their maximum HRRPUA. When many pallets are already burning, the exposure is high, thus, involved parts of the combustible materials reach their maximum HRRPUA almost instantly after their ignition. In the model, this spreading is done cell by cell (see Figure 21).

- The first pallets involved in the fire start are heated only by the heat released by their own combustion (ie. close pallets do not produce an additional heat flux at this time). Their HRR gradually increases slowly until its full development. For these reasons, HRR of first pallets is modelled using the Eurocode 1 part 1-2 procedure. In the model, the overall surface of the pallet burn in order to follow this curve (see Figure 21).

It should be noticed that adjustments of some of these characteristics may be necessary in a CFD model, depending on the grid size. Usually, the smaller the mesh size, the longer the calculation time. However, the use of a coarse mesh may result in a lack of accuracy of the heat transfer calculations along combustible surfaces. As a rule of thumb, the key parameters (ignition temperature and HRRPUA) can be adjusted by preliminary comparisons with the expected fire growth rate of the material involved.

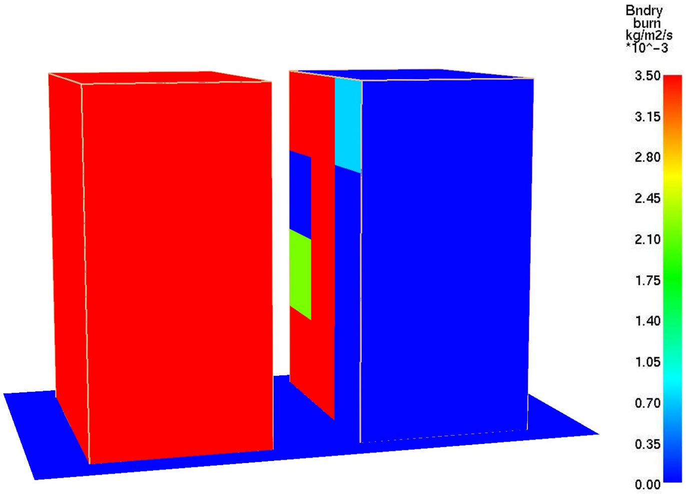


Figure 21 : involved surface (in red) of the fire start (left) and a regular (right) pallet

3.3 Reference fire scenarios

3.3.1 Warehouses

In storage warehouses, a direct assessment of the heat release rate of the combustibles on the basis of experimental or statistical data is difficult because the fires can be very large, of the order of hundreds of megawatts, and there is almost no experimental data with so high HRR values. Besides, the fire development is really dependant of type of stored materials in the racks. Thus, fire spread along the combustible materials and the time dependent heat release rate are calculated by the CFD simulation.

In order to have a conservative design fire scenario for warehouses, it is assumed that plastic products are stored into racks since they have a faster burning than for cellulosic materials, resulting in a faster propagation of the fire between racks. It should be noted that fuel load and HRR were studied during the Flumilog project [4]. Thus, this study considers that each pallet has 25 kg of wood; half of the mass of products contained on the pallet (the wood of the pallet being excluded) corresponds to plastic products and the other half is composed of cellulosic or non-combustible products. Therefore, a single pallet can release 4 117.5 MJ, equivalent to 1525 kW during 45 minutes for a full surface involved pallet (Figure 23).

Concerning the first pallets to burn, a medium growing is adopted until reaching the maximum HRR of 1525 kW/m², identified by the Flumilog method [4]. When 70% of the pallet is consumed, the HRR starts to decrease linearly until the total extinction of the pallet (see Figure 23). For other pallets the HRRPUA is 220 kW/m², it leads to the HRR curve of Figure 23 if all FDS cells of the pallet burn at the same time.

It can be noted that in CFD simulations, each pallet is modeled by a parallelepiped volume of dimensions 1.2×0.8×1.6 m^3, as indicated in Figure 22. The racks are not modelled. The fire is initiated on a single pallet located in the ground level of the storage.

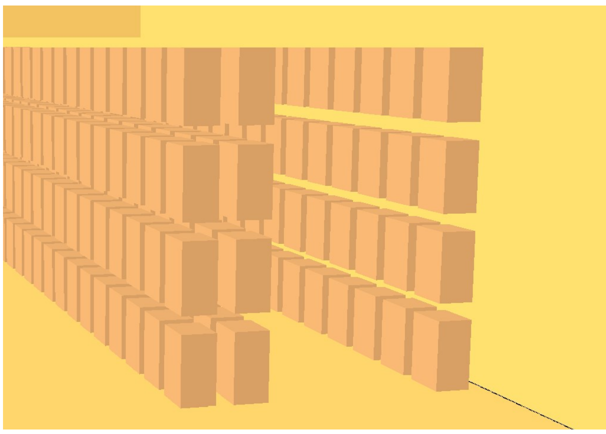


Figure 22: Example and pallets modelling

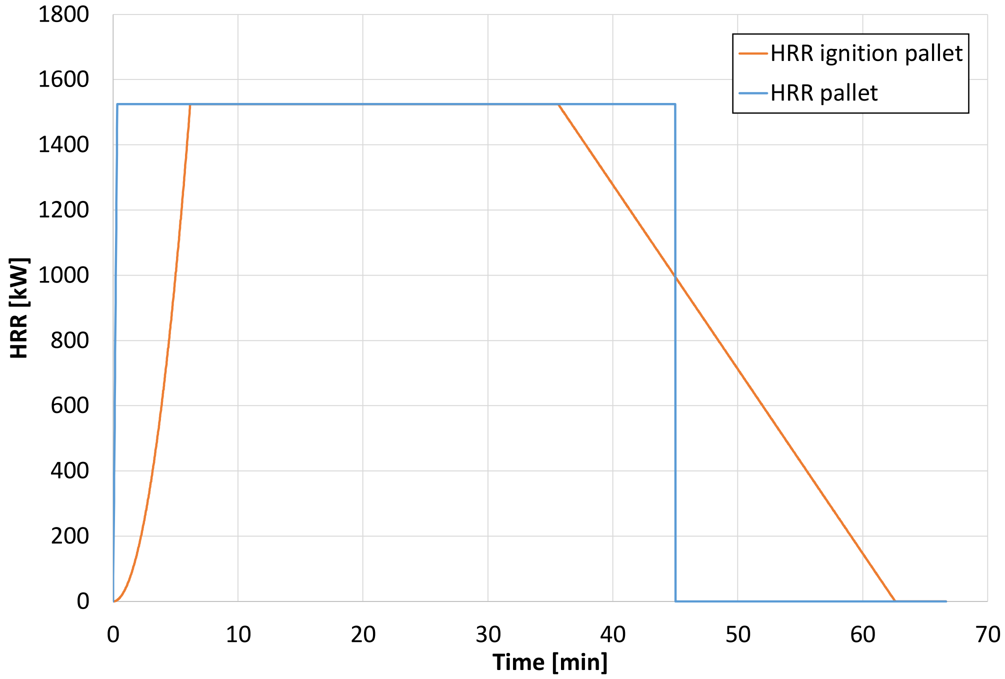


Figure 23: HRR curves of pallet and igniting pallet

3.3.2 Supermarkets

In supermarkets, the distance between the top of the stacking shelves and the building roof is usually quite important. For these reasons, after ignition, the propagation of fire to numerous shelves is unlikely in such type of buildings. It is then assumed that the fire remains localised. It starts in a row shelf and tends to travel to the two row shelves located on each side to the ignition one, as illustrated in Figure 26. Moreover, it is considered here that stored products are mainly foodstuff.

Considered stored goods have a size of 0.8 × 1.2 × 0.4 m^3. In order to have a conservative design fire scenario for warehouses, the same physical properties as those defined for pallets in the previous section are chosen. According to their size, full burning goods can then release 915 MJ, or 340 kW during 45 minutes (see Figure 26).

Ignition of fire is assumed to occur in combustible materials located at the ground level of a shelf. The Heat Release Rate of igniting products corresponds to the curve in Figure 26. A medium fire growth is considered until HRR reaches a plateau of 340 kW. Then, linear decay phase starts when 70% of the mass of the goods have been consumed. For other pallets the HRRPUA is 355 kW/m^2, it leads to the HRR curve of Figure 26 if all FDS cells of the pallet burn at the same time.

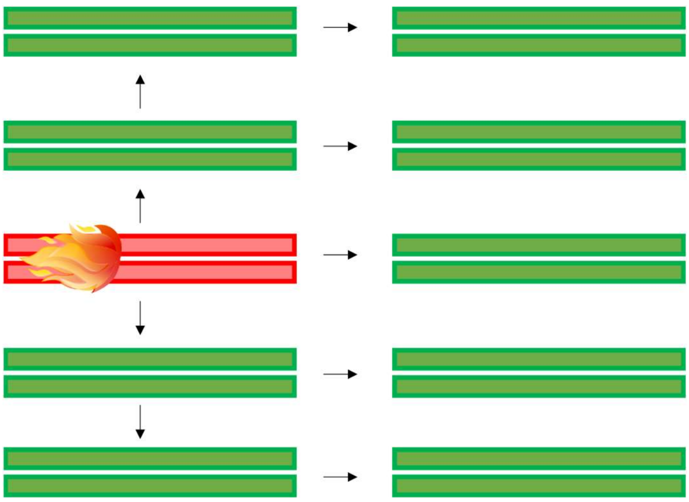


Figure 24: Row shelves igniting first (red) and row shelves involved in fire (green)

It can be noted that in CFD simulations, stored products are considered as rectangular solid of dimensions 0.8×34.4×0.4m³ (building n°1) and 0.8×38.8×0.4m³ (building n°2) running along each storage level of shelves. Double row shelves are modelled lengthwise by a single 0.5 mm thick steel sheet, which separates the products stored on either sides, as indicated in Figure 25.

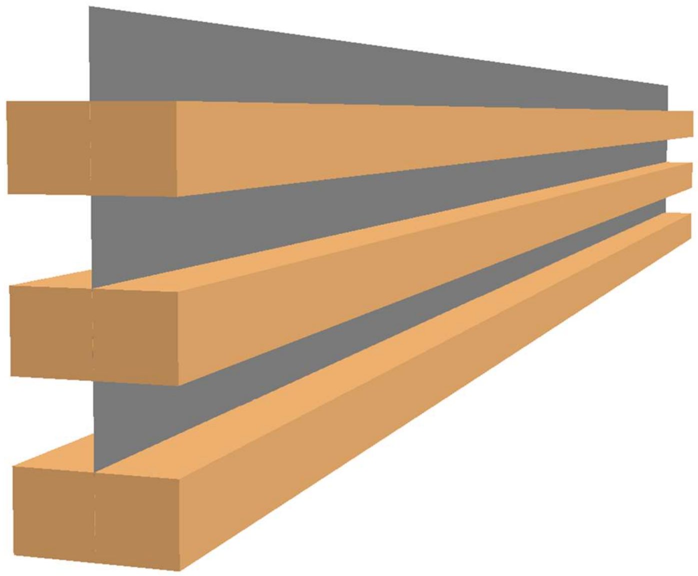


Figure 25: Modelling of double row shelves and stored products

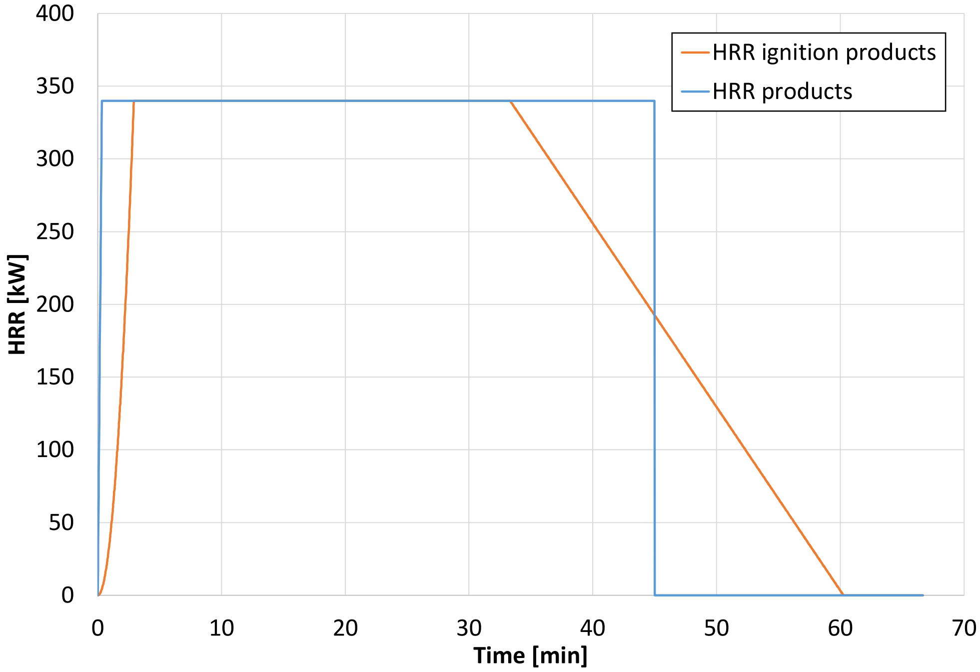


Figure 26: HRR curve of products and igniting products

3.3.3 Industrial buildings

In order to have a conservative design fire for industrial buildings, the fire load is assumed to be represented by a bulk storage of 20 pallets with 1.6m height located on the ground, as illustrated in Figure 27**.** The same type of pallets, as defined for warehouses, is considered here. Then, the total amount of heat released by the full considered bulk storage reaches 82 350 MJ.

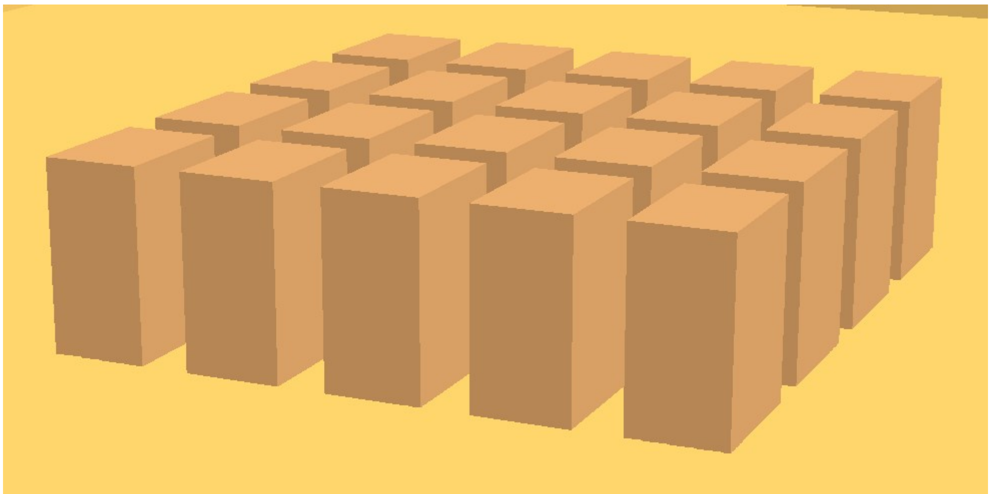


Figure 27: Bulk storage modelling

Priori calculations have shown that spreading from the ignition source to the whole combustible load is not always achieved. Thus, two approaches are tested in order to be on the safe side. The first one consist in the prescription of the heat release rate on the totality of the storage surface. Then, the HRR curve is calculated from the rules given in Eurocode 1 part 1-2 with a maximum HRR of 30.5 MW (see Figure 28). However, this assumption leads to a decrease in the realism of the combustion dynamics.

Thus, another option is to take into account the consumption effect on the combustible materials geometry during the fire. The HRR and mass loss are solved directly by FDS. When all the mass of a mesh size part of the combustible materials is consumed, this leads to its disappearance. Therefore, initially hidden parts of the pallet starts to receive a heat flux and burn. This modeling leads to a lower maximum HRR, but takes into account the total quantity of combustible materials considered in the building. It is intended to be more realistic but it reduces thermal actions received by structural members in comparison with the first approach.

For the first method, HRR is prescribed on all the surface of combustible materials. For the second method, ignition is carried out on a central pallet with the prescribed HRR presented in Figure 23.

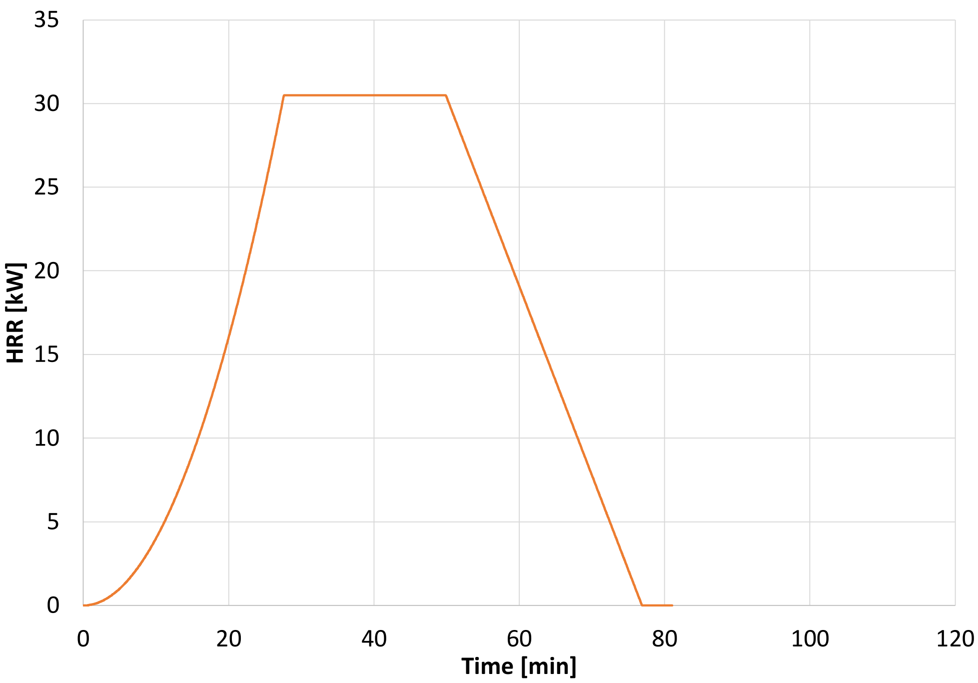


Figure 28: HRR curve calculated from EN1991-1-2 rules

3.4 Selected fire scenarios

Several fire scenarios are defined to investigate:

- the influence of the storage type (and associated combustible materials);

- the location of the fire source on the hot gas layer temperature;
- the spread of hot gases in the considered building and influence on the hot gas temperatures;
- the thermal actions near building walls (where "fusible" systems connecting fire walls could be present).

Considering the reference buildings described in section 2 and the reference fire scenario defined in section 3.3 according to the occupancy type of single-storey buildings targeted in the scope of the project, a total of 24 fire scenarios is defined here. They are listed in the following table. It can be underlined that naming of each fire scenario was decided to define from a letter "W"; "S" or "I" (corresponding to the considered building occupancy: Warehouse, Supermarket or Industrial) followed by a first number (from 1 to 4) corresponding to the considered reference building, and then a second number (1 to 3) associated to the fire source location (in the middle of the building or near a wall).

Table 4: Detail of fire scenarios analysed

Fire scenario	Building	Occupancy type	Location of the fire source
W.1.1	1	Warehouse (rack storage)	In the middle of the single row rack, near one of the longer compartment sides
W.1.2	1	Warehouse (rack storage)	At the end of the central double row rack, near one of the shorter compartment sides
W.1.3	1	Warehouse (rack storage)	In the middle of the central double row rack
S.1.1	1	Supermarket (shelf storage)	At the end of the central double row shelf, near one of the longer compartment sides
S.1.2	1	Hypermarket (shelf storage)	In the middle of a single row shelf, near one of the shorter compartment sides
S.1.3	1	Supermarket (shelf storage)	In the middle of the central double shelf
I.1.1	1	Industrial building (bulk storage)	in a bulk storage, near one of the longer compartment sides
I.1.2	1	Industrial building (bulk storage)	In a bulk storage, near one of the shorter compartment sides
I.1.3	1	Industrial building (bulk storage)	In a bulk storage in the centre of the building
W.2.1	2	Warehouse (rack storage)	At the end of the central double row rack, near one of the longer compartment sides
W.2.2	2	Warehouse (rack storage)	In the middle of the single row rack, near one of the shorter compartment sides
W.2.3	2	Warehouse (rack storage)	In the middle of the central double row rack
S.2.1	2	Supermarket (shelf storage)	At the end of the central double row shelf, near one of the longer compartment sides
S.2.2	2	Supermarket (shelf storage)	In the middle of a single row shelf, near one of the shorter compartment sides
S.2.3	2	Supermarket (shelf storage)	In the middle of the central double row shelf
I.2.1	2	Industrial building (bulk storage)	In a bulk storage near one of the longer compartment sides
I.2.2	2	Industrial building (bulk storage)	In a bulk storage near one of the shorter compartment sides
I.2.3	2	Industrial building (bulk storage)	In a bulk storage in the centre of the building
W.3.1	3	Warehouse (rack storage)	In the middle of the single row rack, near one of the longer compartment sides
W.3.2	3	Warehouse (rack storage)	At the end of the central double row rack, near one of the shorter compartment sides
W.3.3	3	Warehouse (rack storage)	In the middle of the central double row rack
W.4.1	4	Warehouse (rack storage)	In the middle of the single row rack, near one of the longer compartment sides
W.4.2	4	Warehouse (rack storage)	At the end of the central double row rack, near one of the shorter compartment sides
W.4.3	4	Warehouse (rack storage)	In the middle of the central double row rack

The fire scenarios selected in the case study are presented in the following figures.

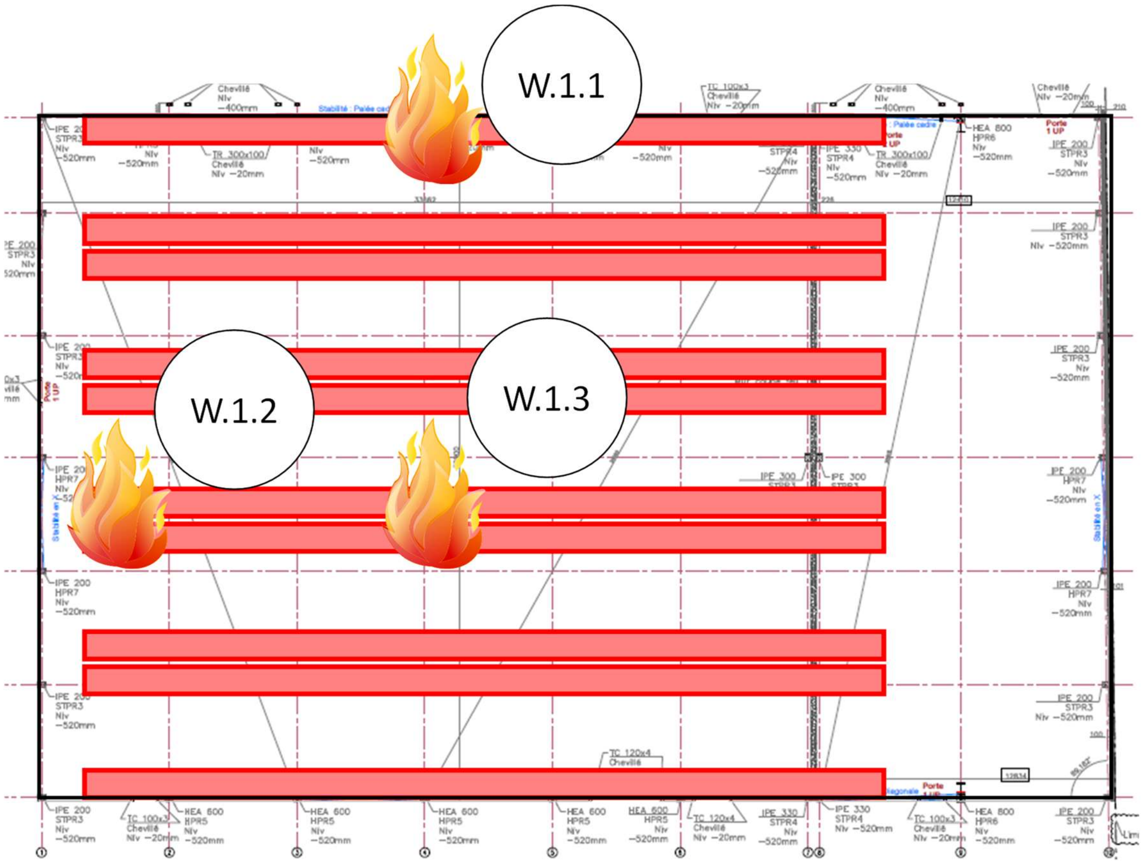


Figure 29: Locations of the fire source for the fire scenarios defined in building n°1 assuming rack storage (warehouse)

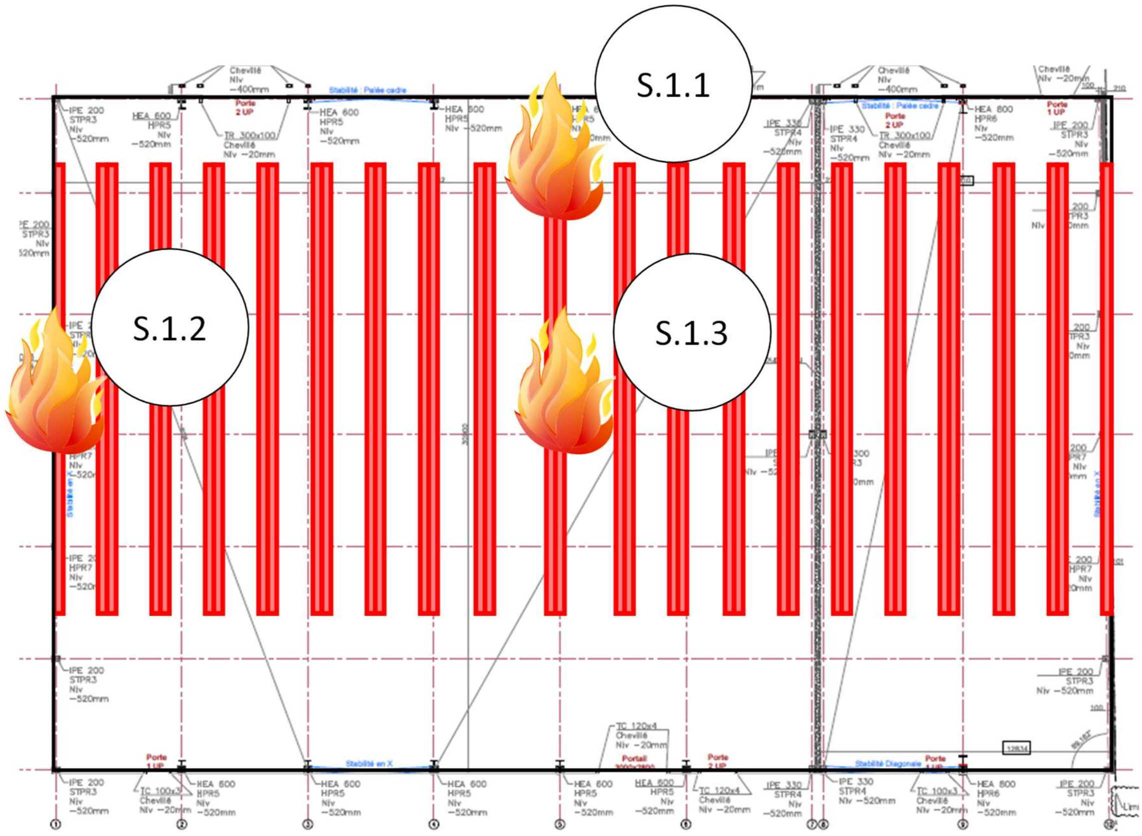


Figure 30: Locations of the fire source for the fire scenarios defined in building n°1 assuming shelf storage (supermarket)

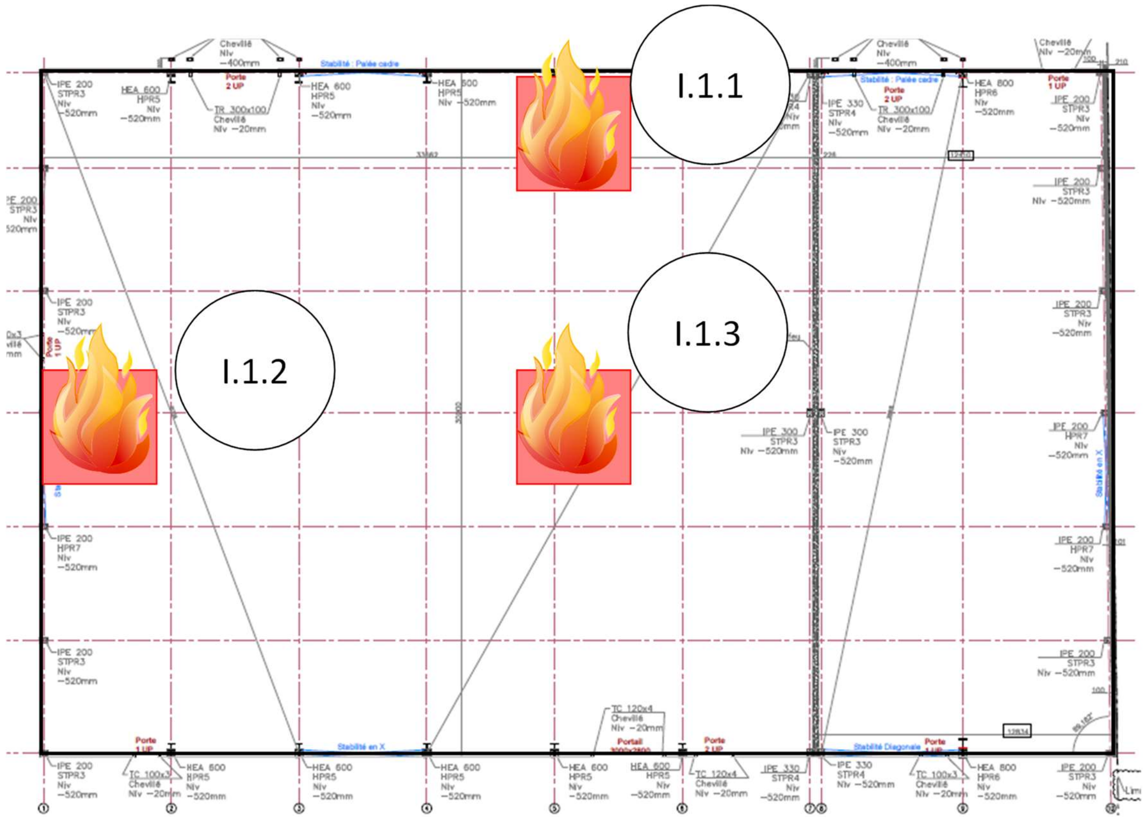


Figure 31: Locations of the fire source for the fire scenarios defined in building n°1 with bulk storage (industrial building)

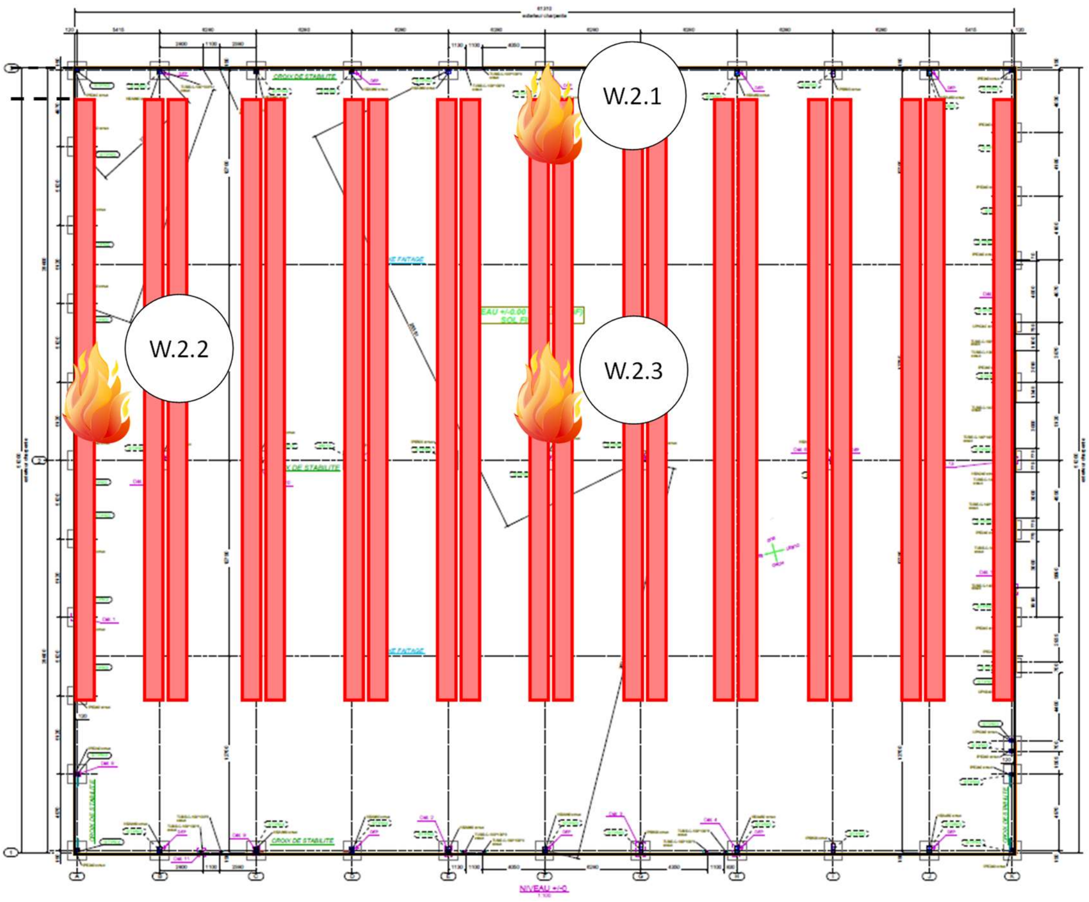


Figure 32: Locations of the fire source for the fire scenarios defined in building n°2 with rack storage (warehouse)

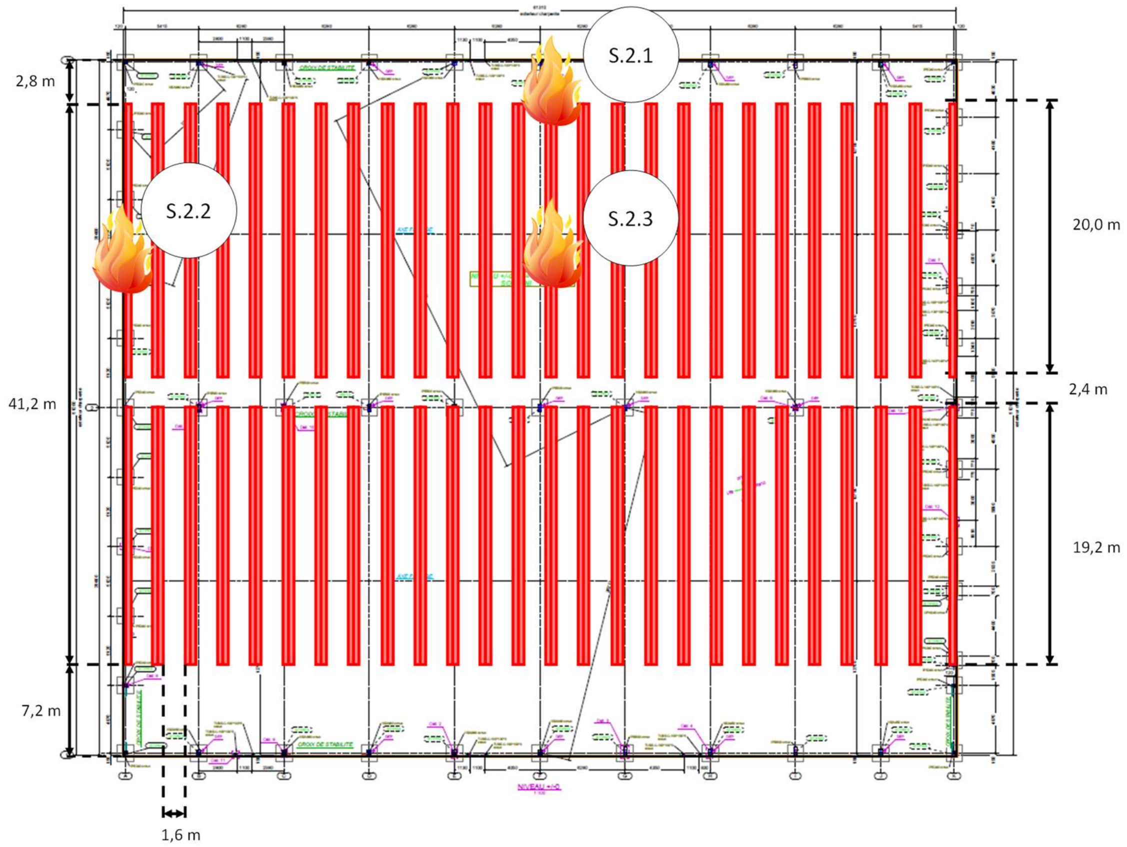


Figure 33: Locations of the fire source for each scenario defined in building n°2 with shelf storage (supermarket)

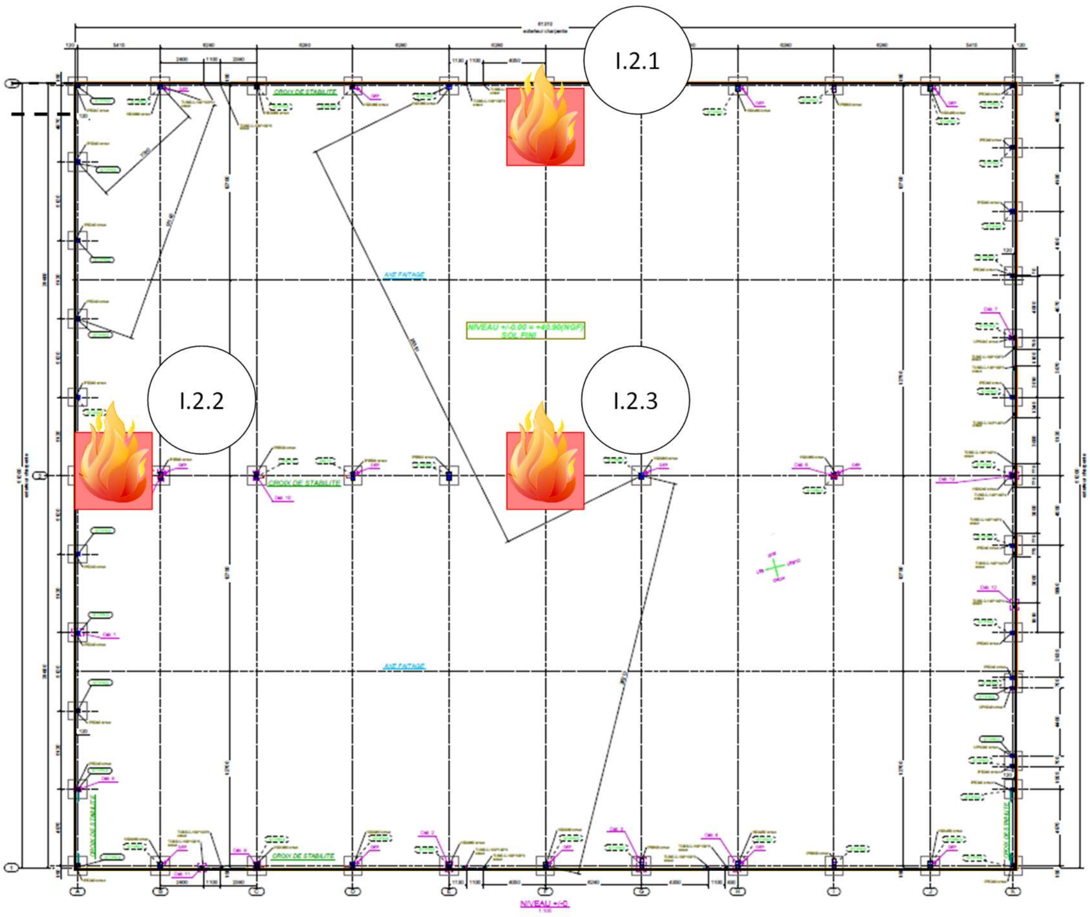


Figure 34: Locations of the fire source for the fire scenarios defined in building n°2 with bulk storage (industrial building)

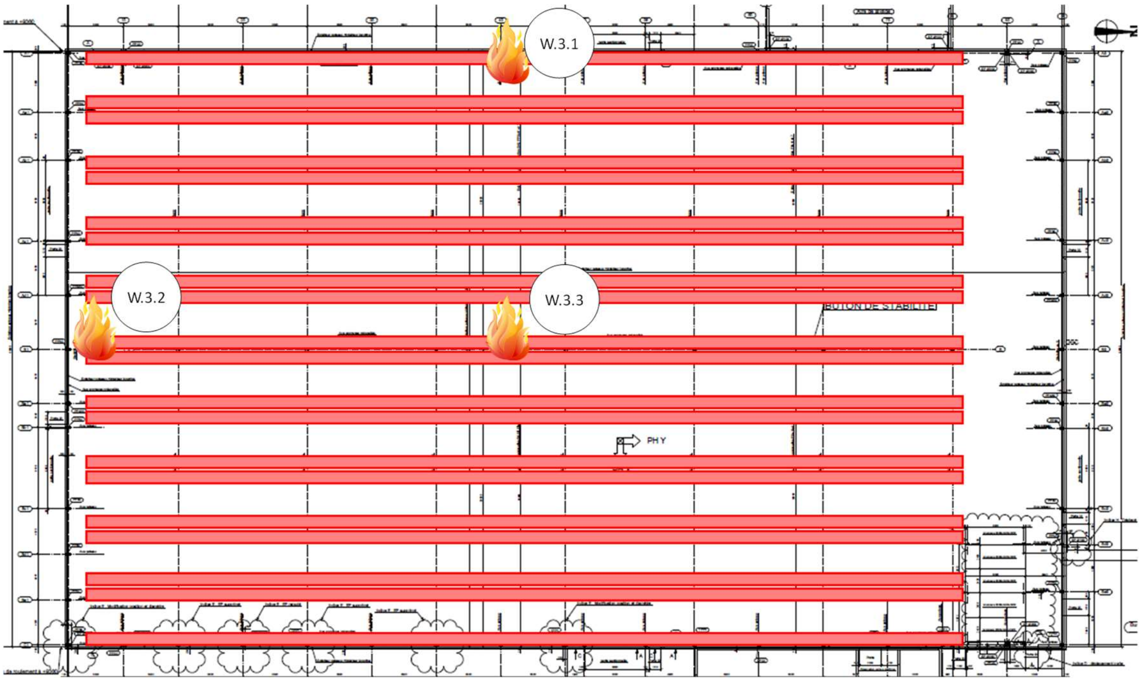


Figure 35: Locations of the fire source for the fire scenarios defined in building n°3 with rack storage (warehouse)

Figure 36: Locations of the fire source for the fire scenarios defined in building n°4 with rack storage (warehouse)

3.5 Numerical fire development simulations

3.5.1 Simulation tools

The Fire Dynamics Simulator (FDS) version 5.5.3, developed by the NIST Building and Fire Research Laboratory [5], is used for this study. It is a three-dimensional computational fluid dynamics (CFD) model designed to predict flows representative of fire situations, which has been the subject of numerous validations [6].

The numerical simulations provide temperature fields of the hot gases, heat fluxes, smoke, and velocity fields as a function of time. All these variables can be visualised using the SmokeView software, also developed by NIST.

3.5.2 Modelling assumptions

The dimensions of the computational domain corresponds to the size of the studied building. One of the FDS modelling of each building type (warehouse, supermarket and industrial building) is shown in Figure 37 to Figure 39.

The different elements modelled are the following:

- A building roof consisting of a single steel sheet with rockwool and waterproofing;
- Boundary walls consisting of double skin cladding with insulation ;
- Smoke vents and skylights ;
- Smoke barriers ;
- Combustible products in storage areas as previously defined;
- Exit doors representing 2% of the floor area of the considered building.

Large gaps corresponding to the purlins height exist between the upper flange of the beam of steel portal frames and the roof. They have a limited influence compared to smoke. So, despite their significant height, the beams constituting the steel portal frames are not modelled.

The modelling assumptions adopted for the FDS simulations are the following:

- Meshes discretising the modelled domains are all cubic with 40 cm edges ;
- Smoke vents throughout the cell are modelled by glass plates disappearing when the temperature of a modelled fusible link reaches 93°C or when the manual release is activated, i.e. 5 minutes after the start of the fire;
- Skylights are modelled by polycarbonate plates disappearing when their temperature reaches 250°C;
- As considers goods and pallets are mainly composed of wood, the chemical reaction considered is that of wood with a heat of combustion of 17.5 MJ/kg and a soot production of 1%;
- Combustible materials stored on racks and on bulk storage are modelled as parallelepipeds, adopting the HRR curves indicated in section 3.3. In addition, an ignition temperature of 300°C, corresponding to the default ignition temperature of wood, which is the first combustible element to ignite in the storage, is adopted.
- Combustible materials stored on shelves are modelled as parallelepipeds running along the length of each shelf level, adopting the HRR curves indicated in section 3.3. In addition, an ignition temperature of 250°C, corresponding to the lower ignition temperature of wood, and considering goods slightly more inflammable, is adopted.
- Ignition of the fire is set on the starting pallet as presented in section 3.3;
- The spread of fire occurs when the surface temperature of a pallet cell reaches the ignition temperature , cell by cell. it then releases 220 kW/m² (355 kW/m² for supermarkets);
- All the pallets modelled in racks and bulk storage can contribute to the combustion;
- As already mentioned, burning of the igniting shelf and the two double-shelves located on both sides only is taking place. All other shelves involve non-flammable materials;

It should be mentioned that active firefighting devices (sprinklers, etc.) are usually present in buildings. However, these devices were not taken into account in simulations.

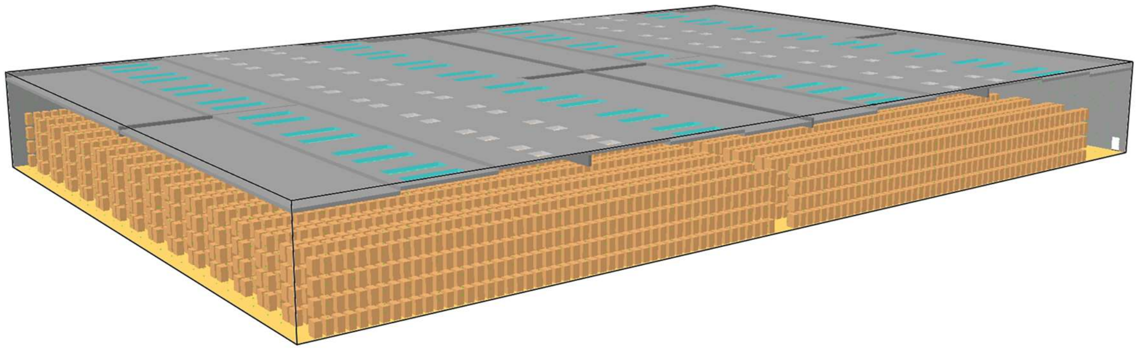


Figure 37: Modelling of a warehouse

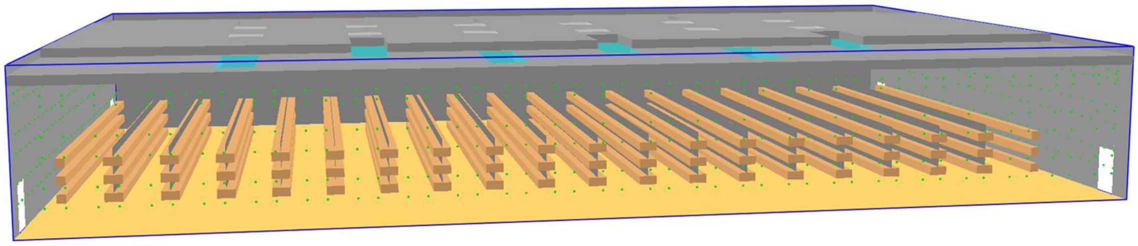


Figure 38: Modelling of a supermarket

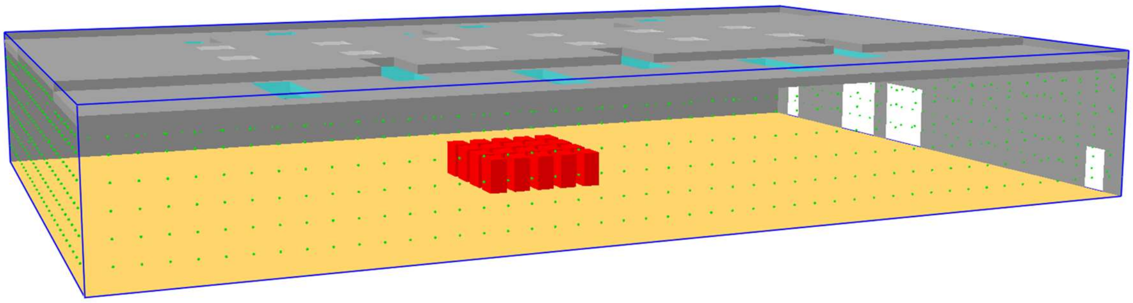


Figure 39: Modelling of an industrial building

4 RESULTS

In this section, only the main results obtained for four scenarios deemed to be representative of results and covering the different building occupancies targeted in the scope of the project (warehouse, supermarket and industrial building) are presented and discussed hereafter. The set of results obtained for the other scenarios are reported in Apppendix A.

It should be noted that the combustion model is based on an infinitely fast reaction; it tends to overestimate the heat released (and thus the temperature) in the case of confined fire. Temperatures over 1200°C are then computed by FDS, which is unrealistic. In real fires, the chemistry is an important process where multiple reactions occur, depending on the ratio oxygen / combustible. For fire inside a building, the quantity of oxygen is often limited (compared to combustible). It leads to incomplete combustion where soot, carbon monoxide and other products are released with the consequence of a lower heat released. As a consequence, the gas temperature in a fire compartment is in the range 900°C-1000°C and may punctually (in space and in time) reach 1100°C or even 1200°C (it was observed in the Flumilog project, see Figure 40). Therefore, temperatures are capped to 1000°C.

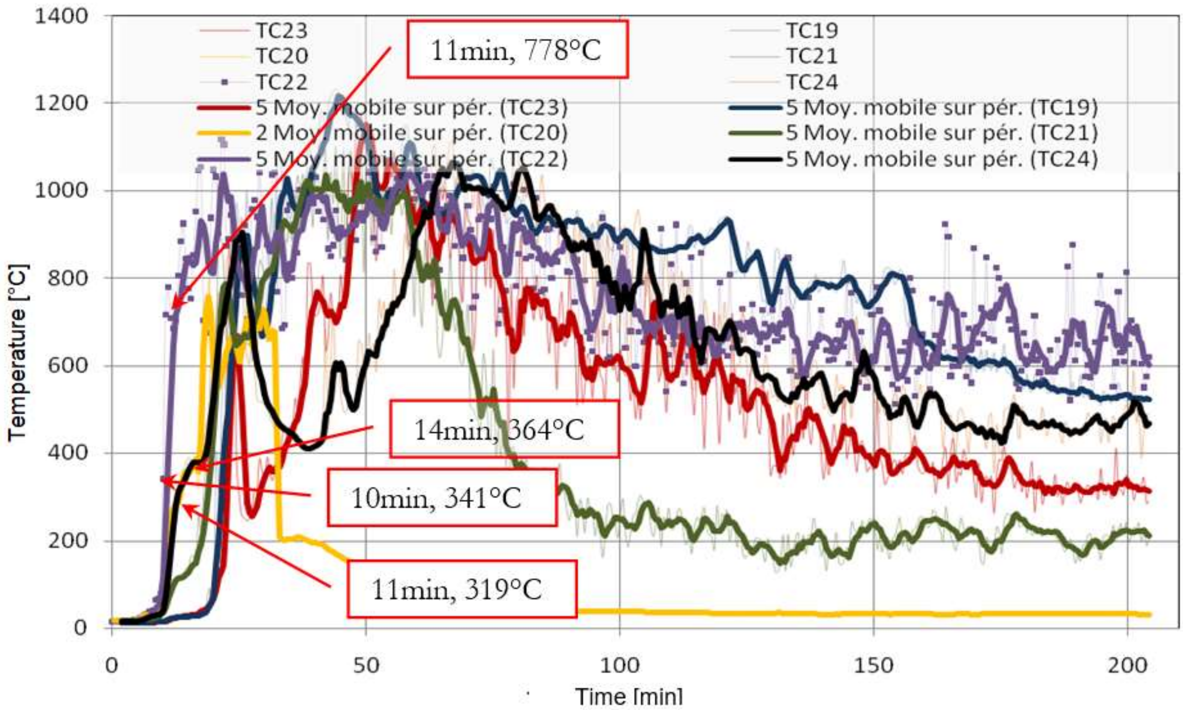


Figure 40: Gas temperature inside a rack measured during the full-scale test of the Flumilog project [4]

In addition to gas temperatures inside the building, it should be noted that radiative heat fluxes affecting the steel structures were also calculated, but none is presented in this report.

4.1 Scenario W.1.1

This scenario concerns a 1400m² warehouse with a racking storage system. The source of fire is positioned in the middle of a single row rack located along one of the longer building walls.

The calculated HRR is shown in Figure 41. The plan views in Figure 42 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. Once the fire is ignited, a fast spreading of the fire can be observed. The flashover starts at 19 minutes (see Figure 42c and Figure 42d). This phenomenon can be explained by the short height existing between the top of the storage and the roof as well as the small free volume inside the building. Indeed, hot gases produced by the fire quickly fill the free volume in the upper part of the warehouse, including the third racks level. At the same time, their temperature increasing, the third level pallets ignite one after the other. Then, most of stored pallets are ignited after 25 minutes. It should be noticed that, although the openings area is important (9% of the roof surface), the natural smoke extraction flow is not enough to efficiently evacuate all the heat generated by the fire. After 1 hour, the amount of combustible materials gradually decreases with the pallets combustion, until the total extinction of the fire at 76 min due to a lack of combustible.

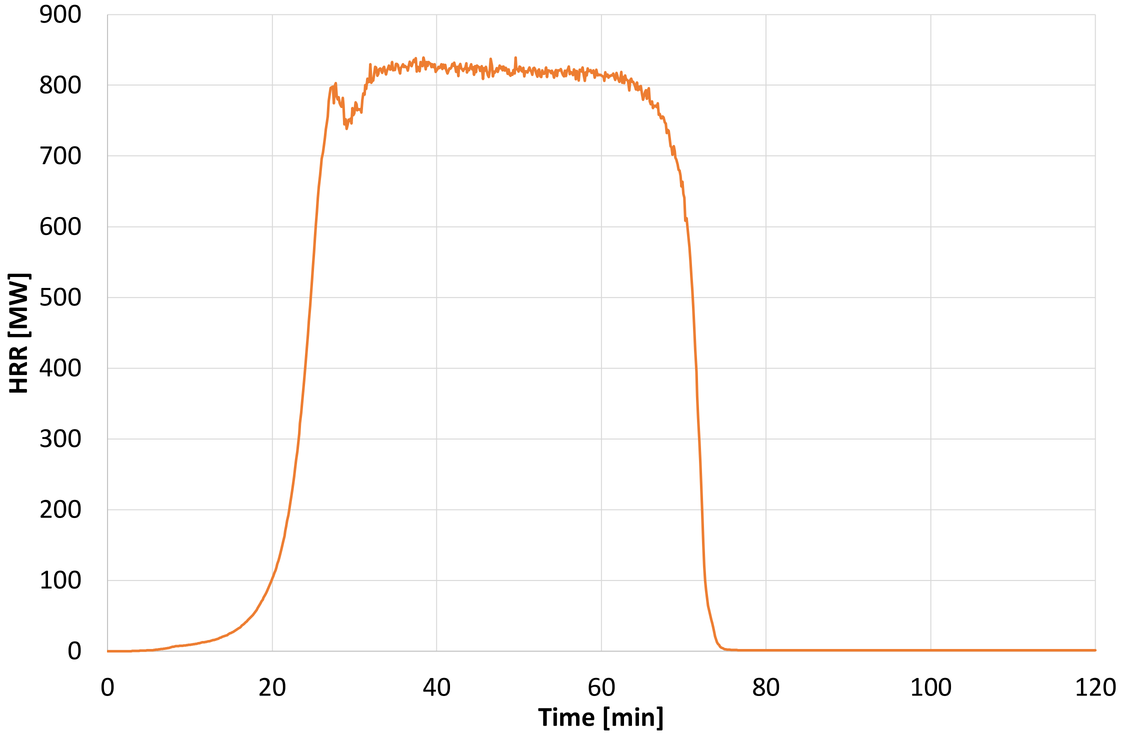
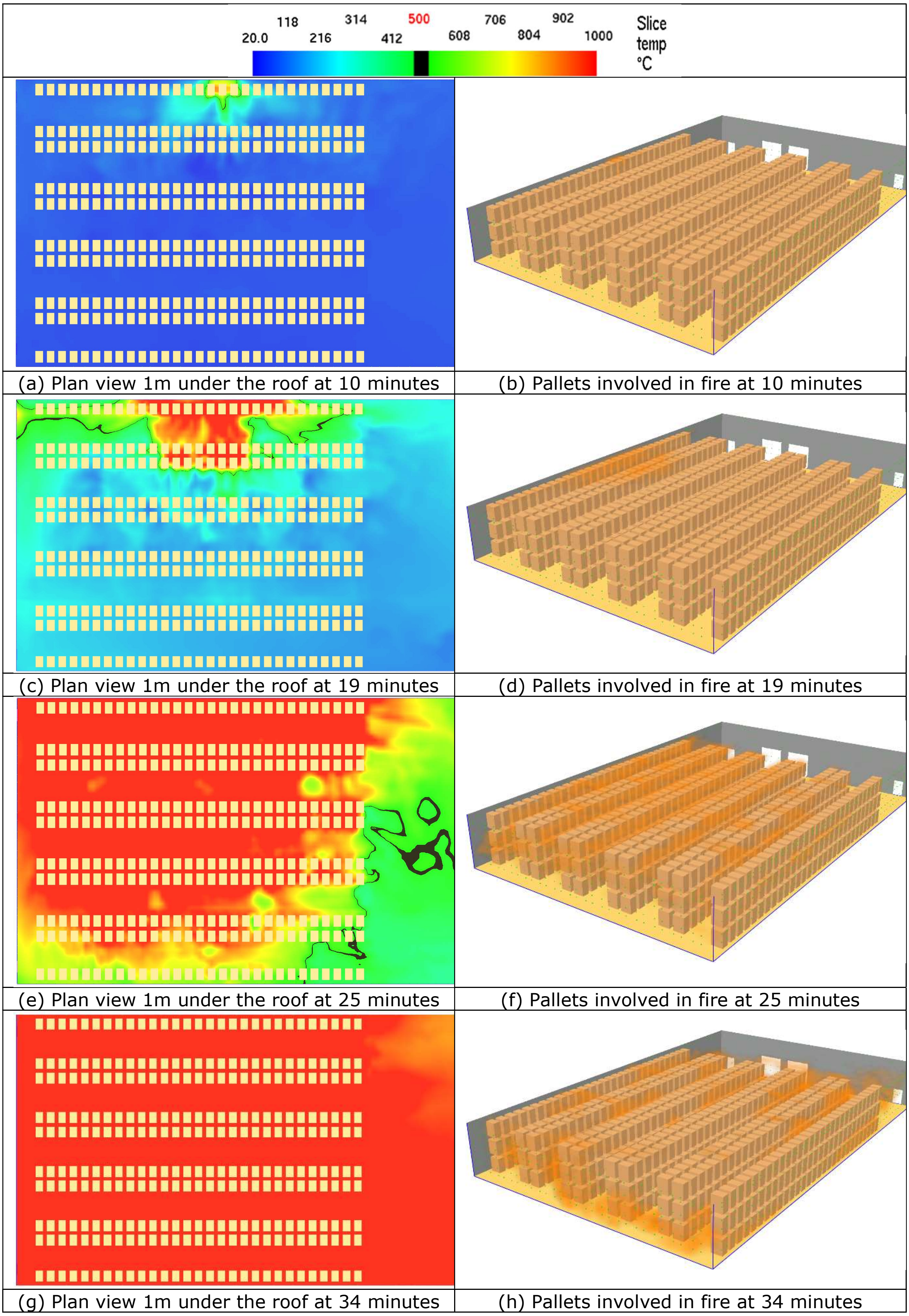


Figure 41: HRR calculated for the scenario W.1.1



(a) Plan view 1m under the roof at 10 minutes | (b) Pallets involved in fire at 10 minutes

(c) Plan view 1m under the roof at 19 minutes | (d) Pallets involved in fire at 19 minutes

(e) Plan view 1m under the roof at 25 minutes | (f) Pallets involved in fire at 25 minutes

(g) Plan view 1m under the roof at 34 minutes | (h) Pallets involved in fire at 34 minutes

Figure 42: Temperature fields under the roof and surfaces involved in the fire

Figure 43 shows the gas temperatures calculated at 1m under the roof, directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 45). During the first ten minutes, it can be noted that only the gas temperatures near the fire source are quickly increasing. The gas temperatures calculated at thermocouples Tf and T1 reach 650°c approximately at 10 min, while the other thermocouples (T2 to T5) give gas temperatures lower than 100°C. Then, the gas temperatures increase progressively in other parts of the building with the spread of fire between the pallets. Thus, thermocouples T2, T3, T4 and T5 show similar temperature rises, but delayed over time. This phenomenon is commonly observed in rack storage if the fire starts at the base: flames goe vertically to the upper side, then spreads toward the edge of racks. During this phase, the shape of the fire area seems to be a “V” (see Figure 44). It occurs also when the fire spreads to an adjacent rack by thermal radiation. At these thermocouples, a gas temperature over 650°C is reached after 18 to 25 minutes, respectively. The highest gas temperature of 1000°C is reached first at thermocouples Tf and Tf (at 18 minutes), then at thermocouples T2, T3, T4 and T5, as the flashover appears in this fire scenario. At the beginning, the fire is relatively small, hot gases dilute in the cell volume and there is no real hot layer. When the fire grows, openings (as natural smoke vents) are not enough to evacuate all hot gases, thus leading to a hot gas layer. That layer can impact and ignite the upper part of racks. After 34 minutes, the hot gas layer is uniformely distributed in the whole building: across the building height and under the building roof (see Figure 42g and Figure 47). Then, gas temperatures starts to decay at 76 min as the combustible materials load is consumed.

It should be noted that the compliance of performance criteria for structural safety, serviceability and durability of structures provided for cold design strongly affects the temperature level from which structural collapse can occur in single-storey steel framed buildings. This temperature, according to extensive studies conducted in numerous research projects [7], is over 650°C with common portal frame systems. Obviously, the risk of partial or full structural collapse depends of the fire-impacted structural area, in particular the extent of the area with fire-damaged members. Basing on this temperature level, a global structural collapse will inevitably happen with this fire scenario.

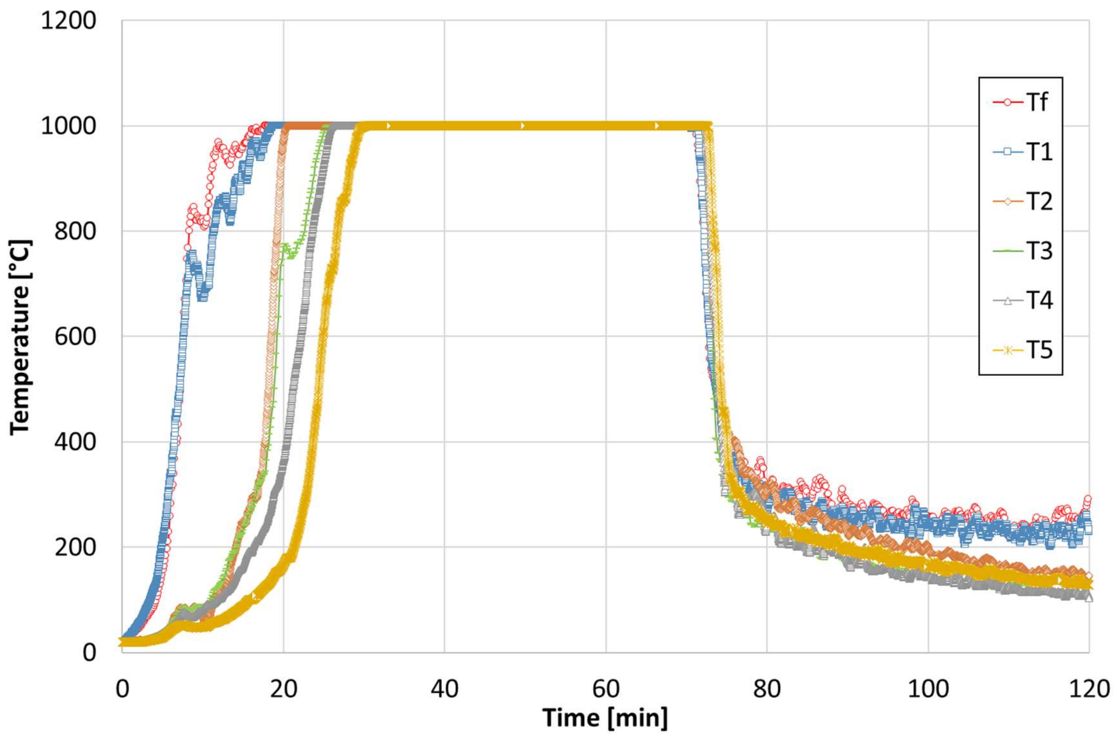


Figure 43: Gas temperature at different locations under the roof

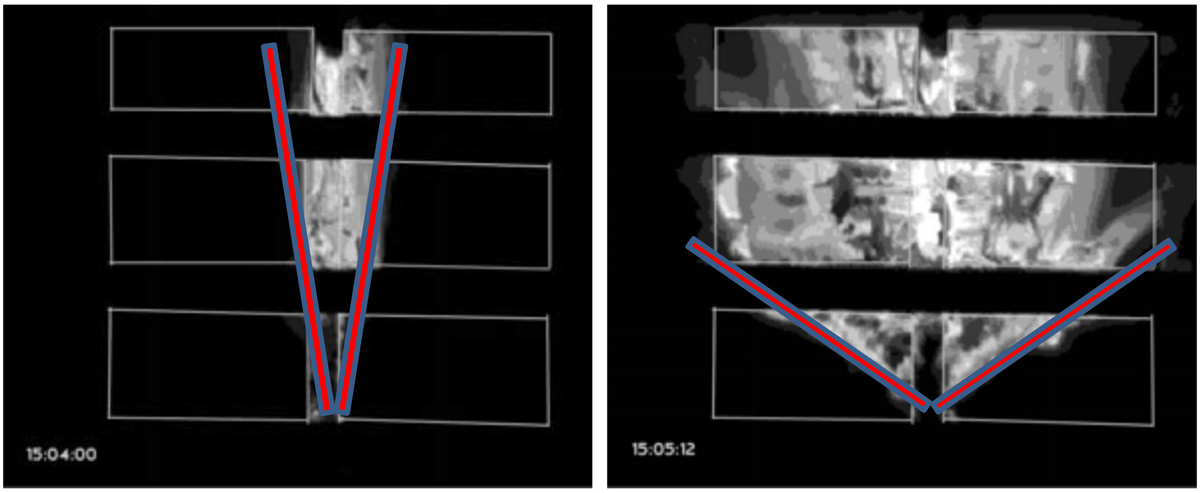


Figure 44: Flame spreading inside a rack

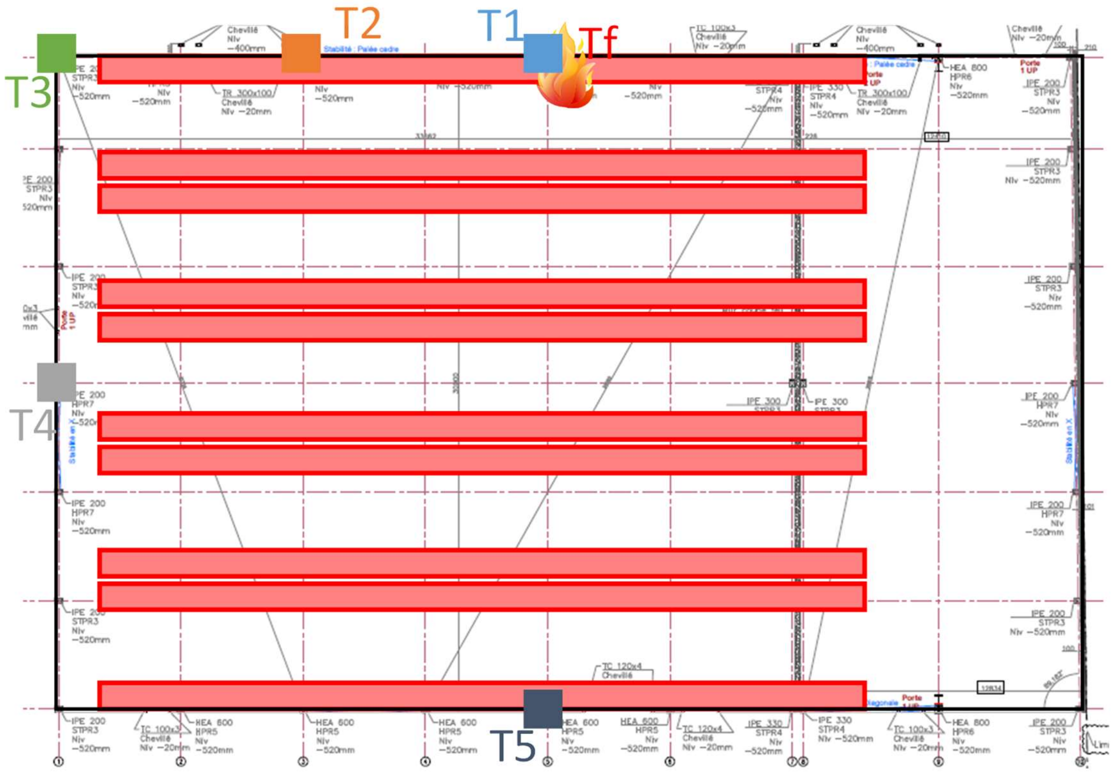


Figure 45: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple T1, are shown in Figure 46. It can be noted that temperatures reached along the height change significantly during the whole time of the fire. Although the gas temperature rapidly increases above 5 m height (with the development of a hot gas layer under the roof), it increases more slowly at the lower parts. At 19 minutes, the temperatures rise accelerate until gas temperatures reach everywhere the highest temperature of 1000°C after flashover is reached (from 23 to 27 minutes approximately).

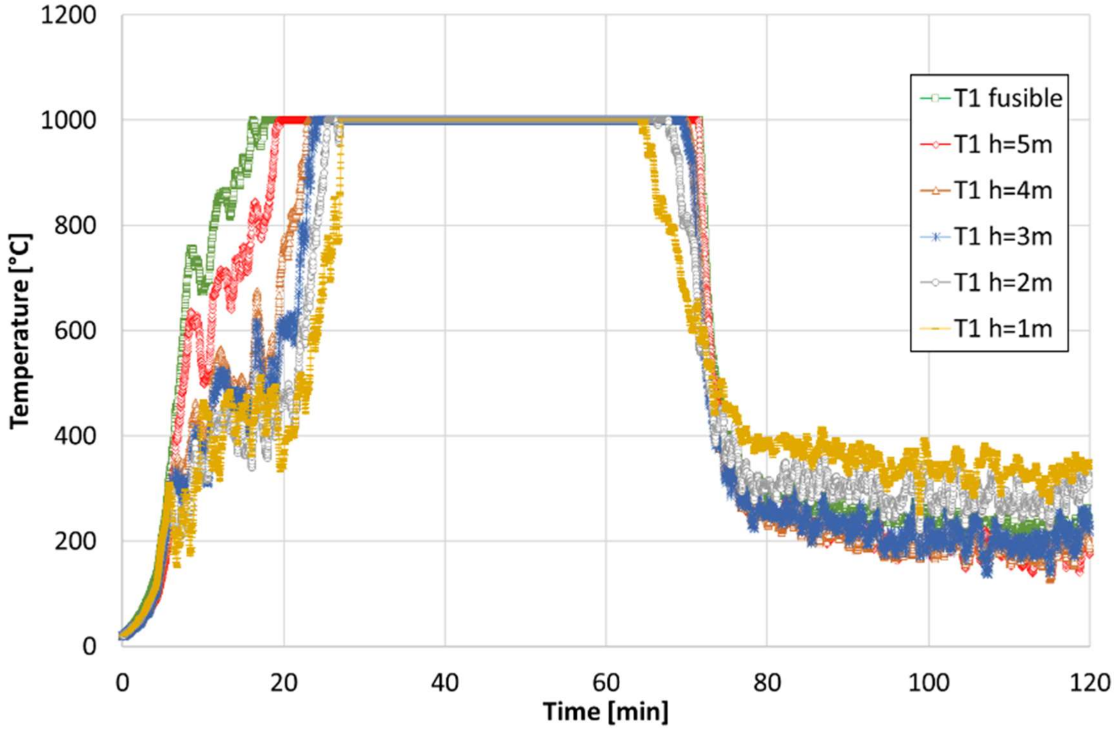
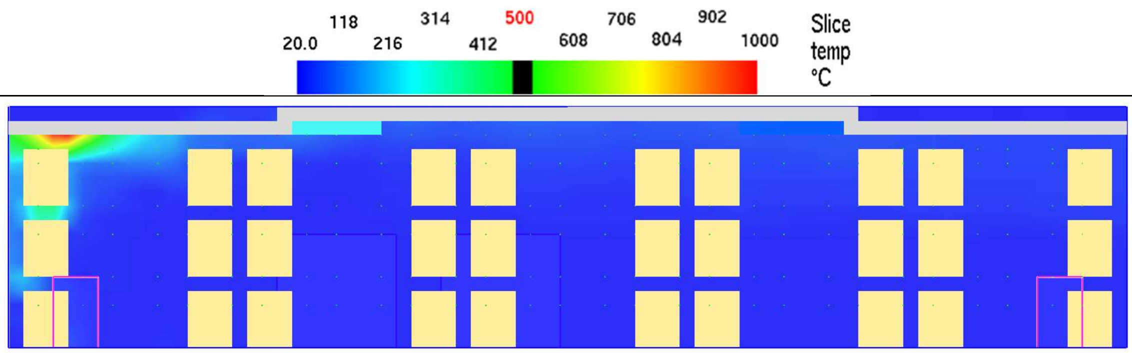
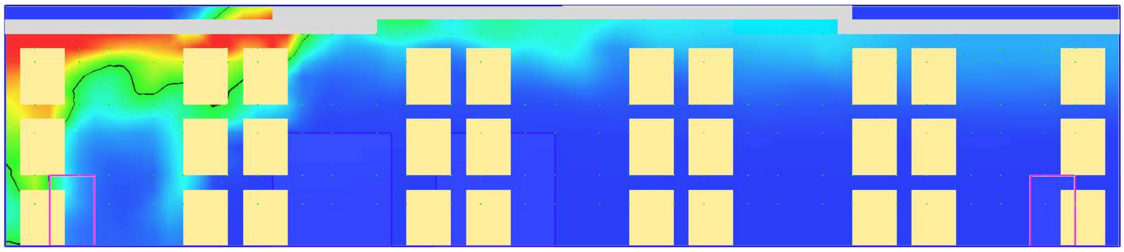


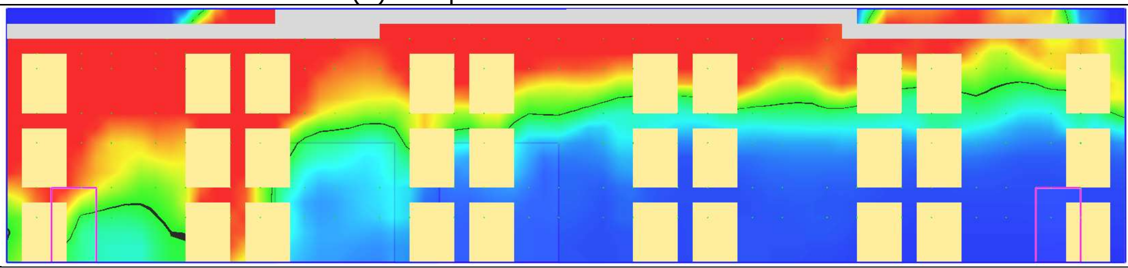
Figure 46: Gas temperatures versus time across the wall height at the location of thermocouple T1



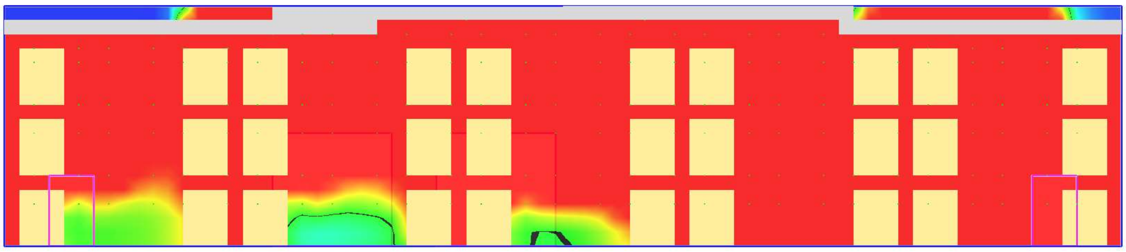
(a) Temperature field at 10 minutes



(b) Temperature field at 19 minutes



(c) Temperature field at 25 minutes



(d) Temperature field at 34 minutes

Figure 47: Temperature fields in the plan of the steel portal frame the nearest of the fire source

4.2 Scenario S.1.2

This scenario concerns a 1400m² supermarket with a shelf storage system. The source of fire is situated in the middle of a single row shelf placed along one of the shorter building walls.

The calculated HRR is shown in Figure 48. In this case, the flashover does not occur. Indeed, the lower density of combustible materials coupled with the roof height leads to an important dilution of hot gas. Furthermore, the roof opening allowing the evacuation of smokes and hot gases outside the building is too important compared to the HRR. Then, a large quantity of heat is evacuated here. The fire propagation occurs gradually and is driven by radiative heat fluxes. At 22 minutes, the three shelves that can be involved in fire (as defined in the chosen scenario) are partially burning (see Figure 49d). Then, all the combustible materials on shelves are burning at 49 minutes. Finally, the first combustible materials involved in fire stop burning, leading to a decay phase of the fire. The amount of combustible materials gradually decreases with the combustion until the total extinction of the fire at 90 minutes.

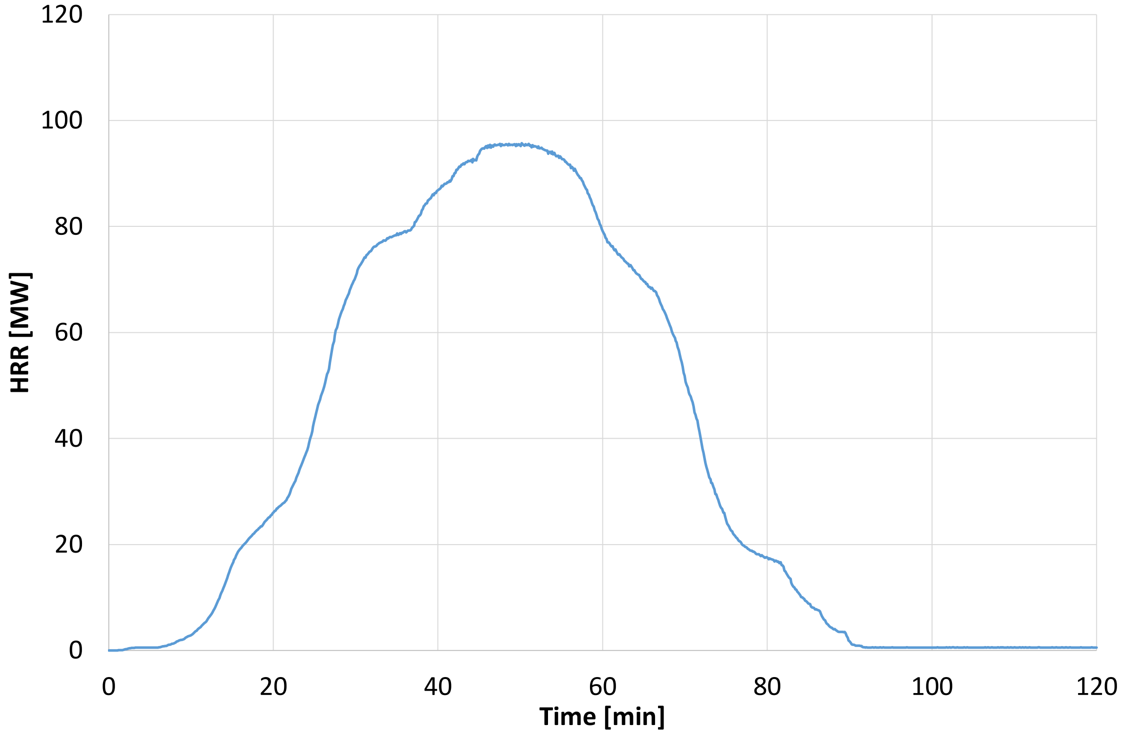
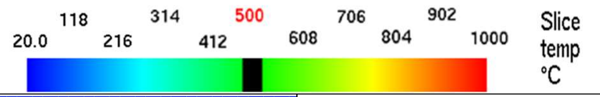
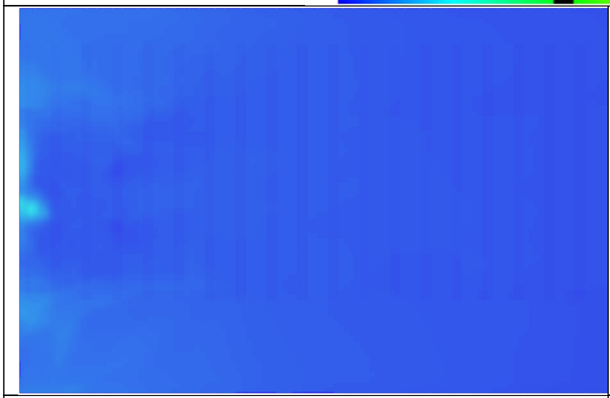
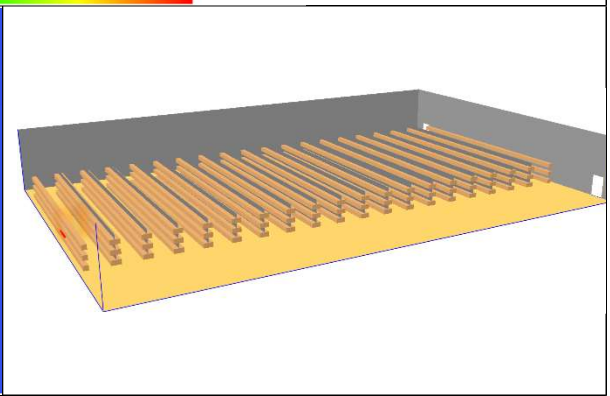


Figure 48: HRR calculated for the scenario S.1.2

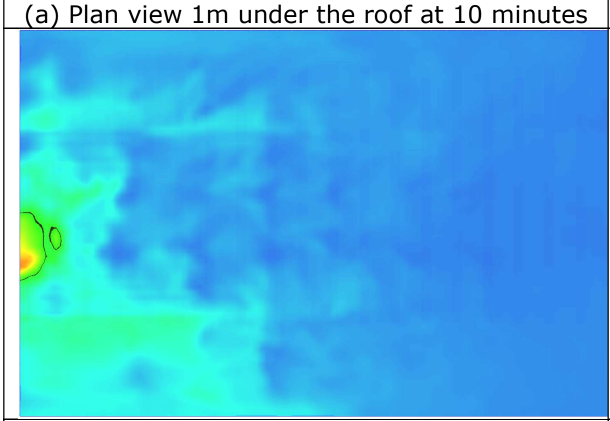




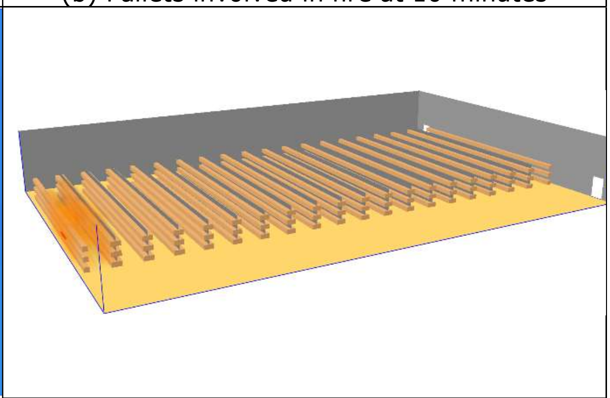
(a) Plan view 1m under the roof at 10 minutes



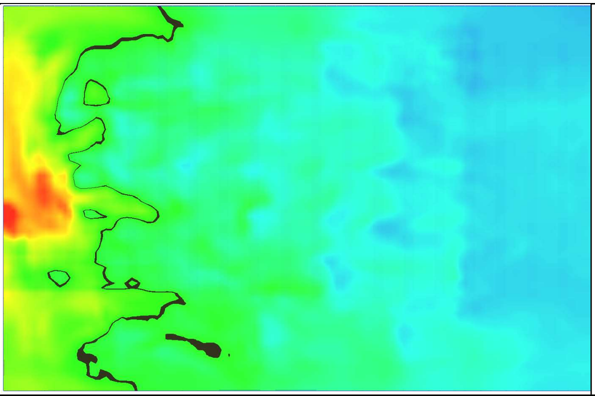
(b) Pallets involved in fire at 10 minutes



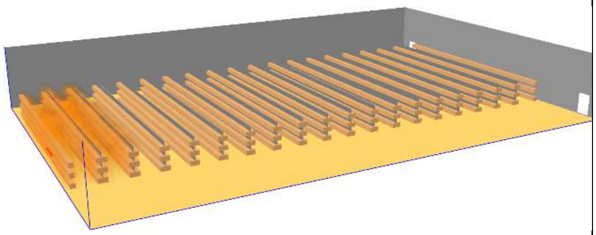
(c) Plan view 1m under the roof at 22 minutes



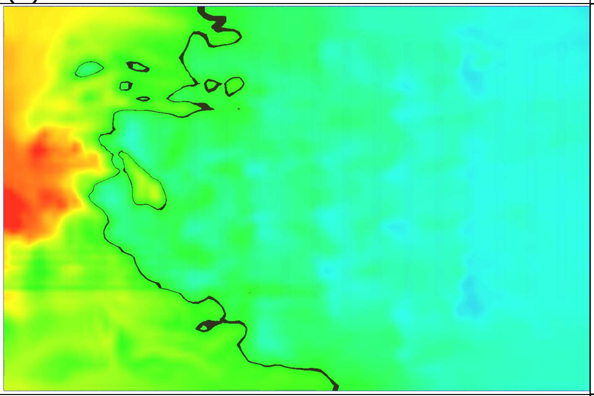
(d) Pallets involved in fire at 22 minutes



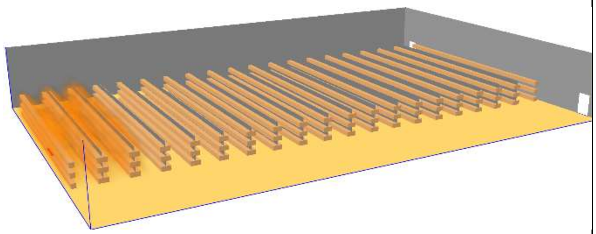
(e) Plan view 1m under the roof at 35 minutes



(f) Pallets involved in fire at 35 minutes



(g) Plan view 1m under the roof at 49 minutes



(h) Pallets involved in fire at 49 minutes

Figure 49: Temperature fields under the roof and surfaces involved in the fire

Figure 50 shows the gas temperatures calculated at 1m under the roof, directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present) close or far away from the fire source (as indicated in Figure 51). During the first 28 minutes, only the gas temperatures near the fire source are quickly increasing. The temperatures calculated at thermocouples Tf and T4 reach 650°c approximately at 22 min while the other measurement points give gas temperatures lower than 250°C at the same time. Then, the gas temperatures increase progressively in parts of the building the nearest of the fire source, while heating remains limited in the other parts. It should be noted that the gas temperatures at thermocouple Tf and T4 reach the highest value of 1000°C after 39 minutes. At 50 minutes, the highest temperatures reached at thermocouples T1, T2, T3 and T5 are 400, 700, 800 and 280°C respectively. After 60 minutes, gas temperatures start to decay as the combustible materials load is consumed.

Basing on a critical temperature of 650°C for steel portal frames, it should be noted that a localised structural collapse may occur with this fire scenario.

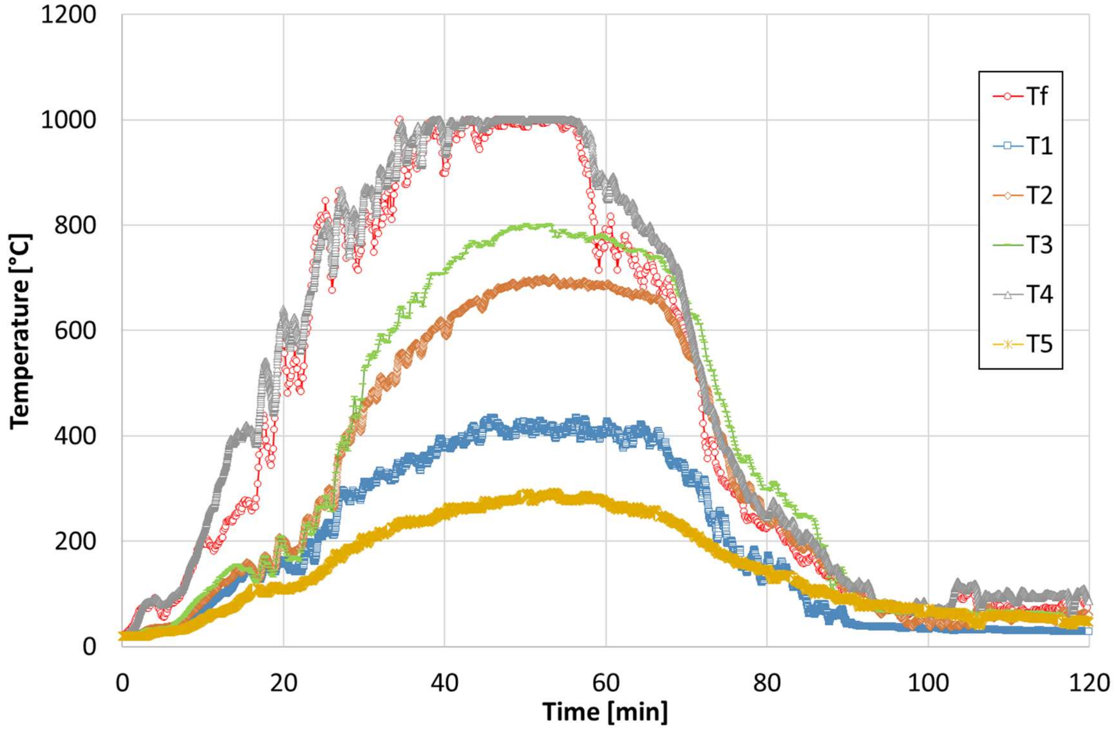


Figure 50: Gas temperature at different locations under the roof

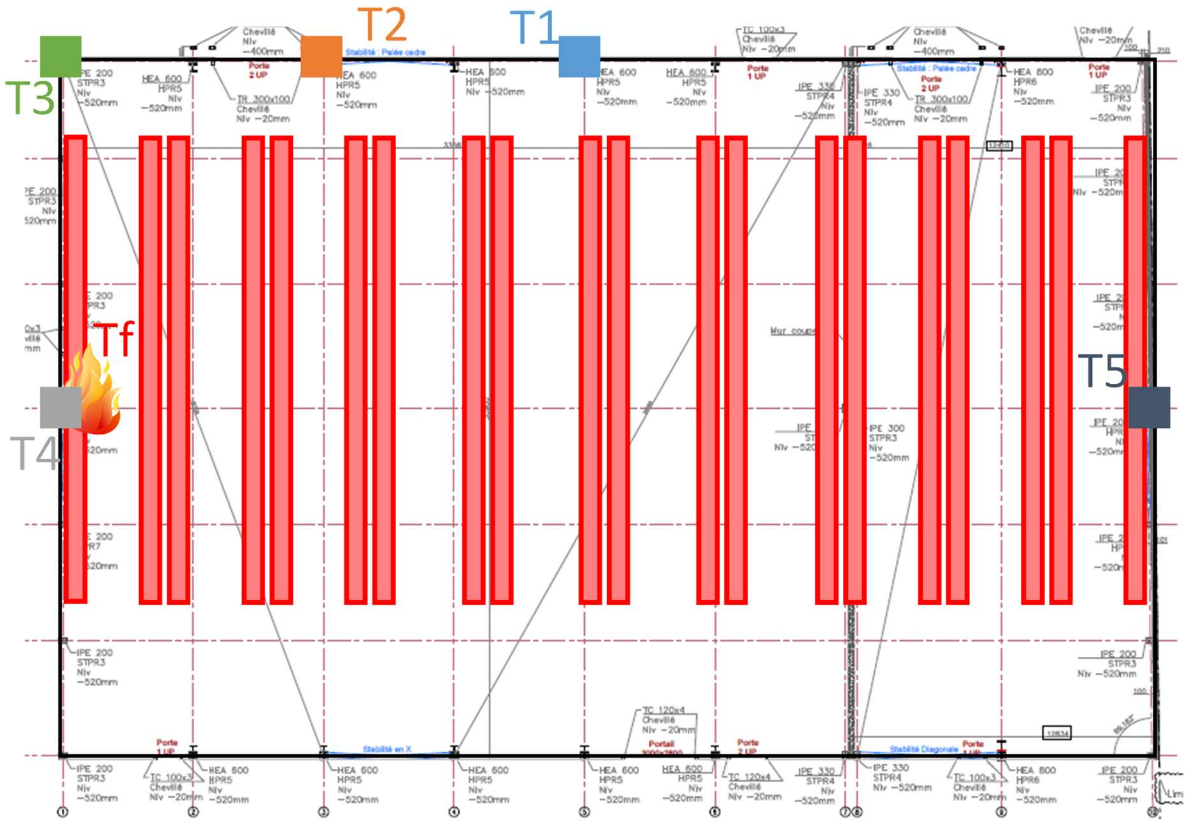


Figure 51: Temperature measurement point locations

Gas temperatures calculated at different wall heights nearest the fire source, at the same location as thermocouple T4, are shown in Figure 46. It can be noted that in the early times of fire, the hot gases are higher at the roof level. Then, they are uniformely distributed along the height after 20 minutes, meaning that there is a stratification phenomenon (the whole volume is divided in two zones).

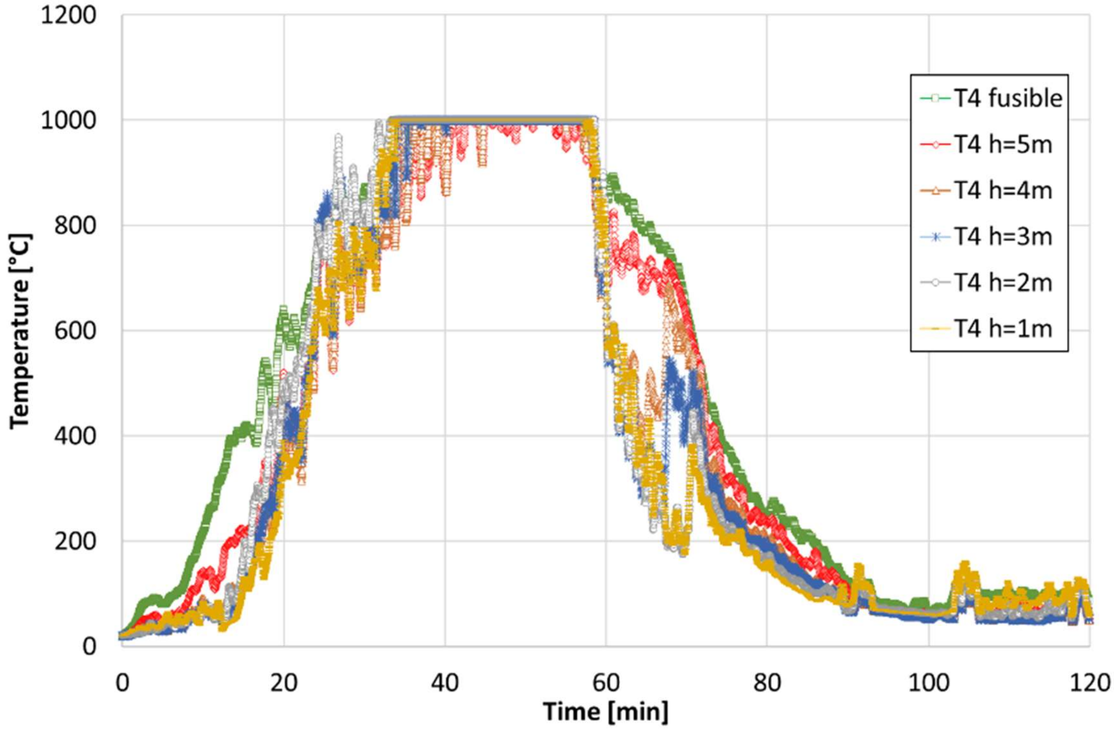
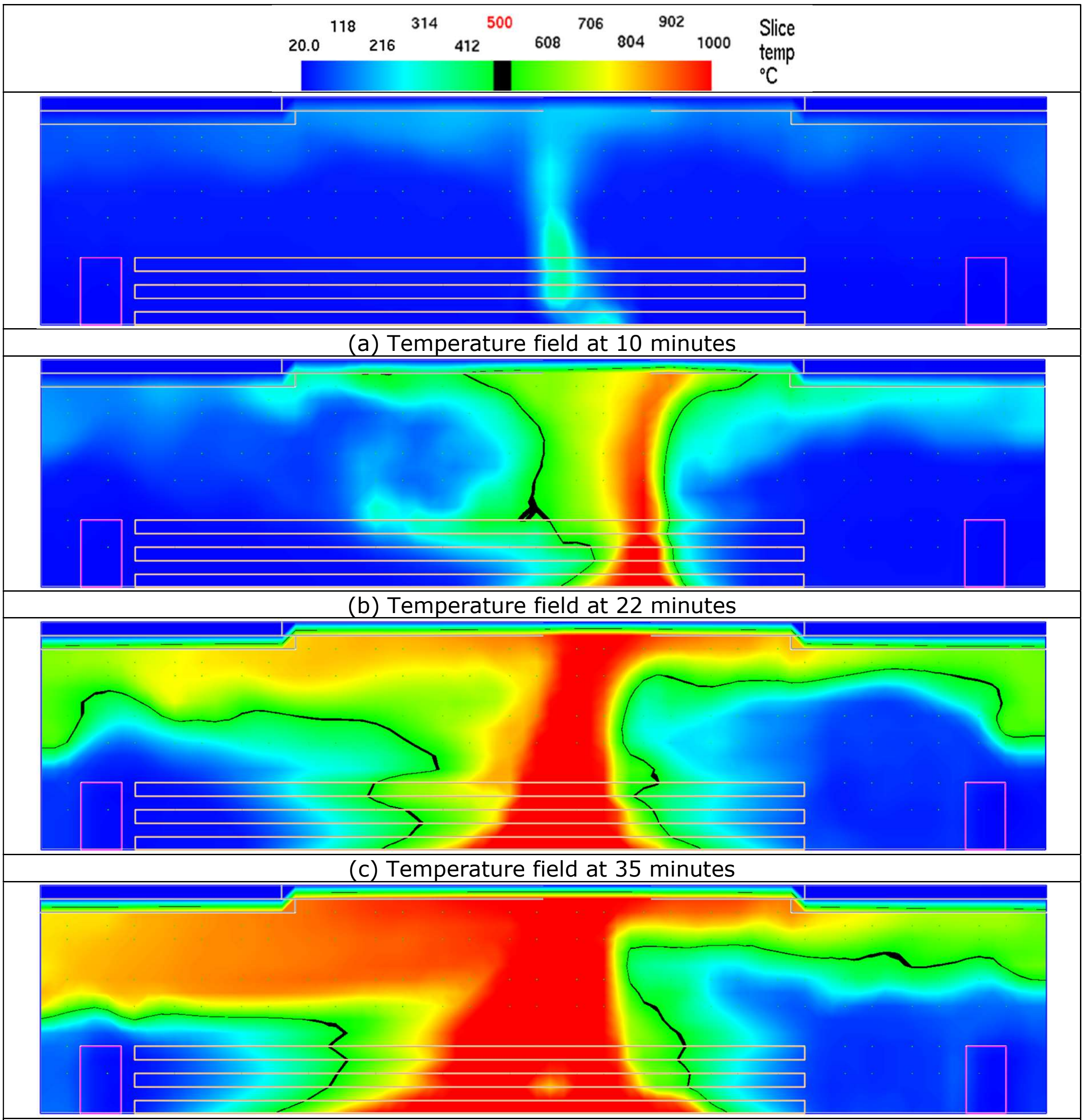


Figure 52: Gas temperatures versus time along the wall height at the location of thermocouple T4



(a) Temperature field at 10 minutes

(b) Temperature field at 22 minutes

(c) Temperature field at 35 minutes

(d) Temperature field at 49 minutes

Figure 53: Temperature fields in the plan of the steel portal frame the nearest of the fire source

4.3 Scenario I.1.2

This scenario concerns a 1400m² industrial building with a bulk storage, located near one of the shorter building walls.

The calculated HRR is shown Figure 54. The plan views in Figure 52 show the temperature development at 1m below the roof at four different times. In this scenario, the quantity of heat produced is not important enough to obtain a large zone of hot gases under the roof. Only the area near the combustible reaches temperatures over 500°C. After 45 minutes, the fire decays due to a lack of combustible.

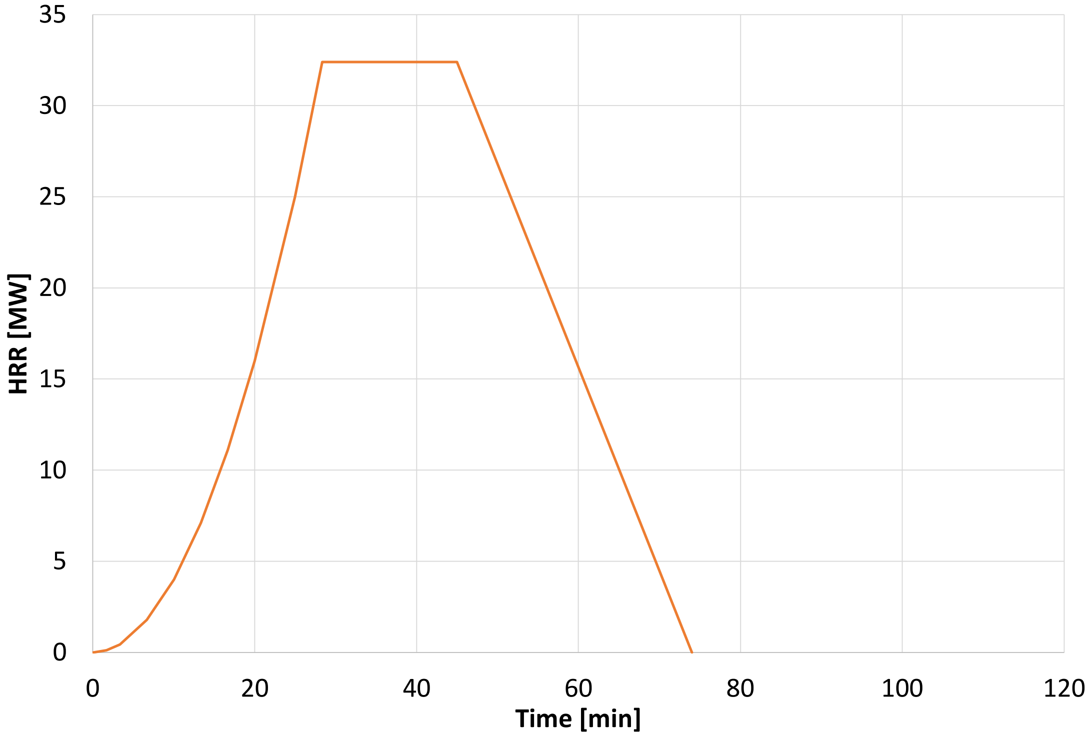
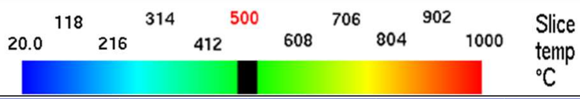
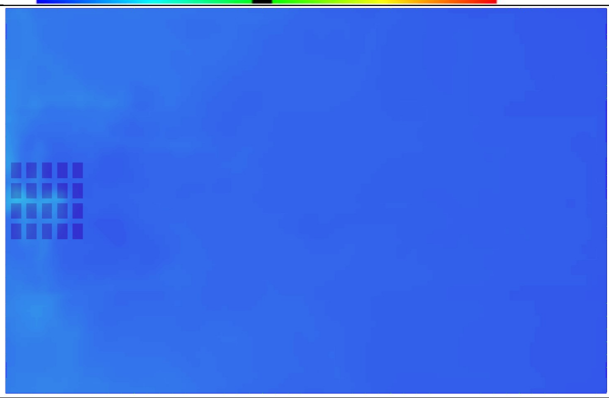
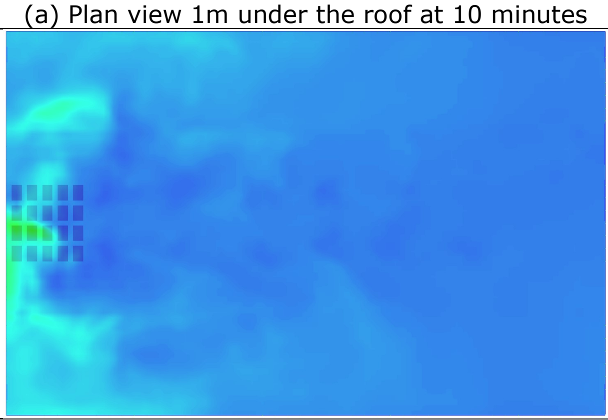


Figure 54: HRR calculated for the scenario I.1.2





(a) Plan view 1m under the roof at 10 minutes



(c) Plan view 1m under the roof at 20 minutes

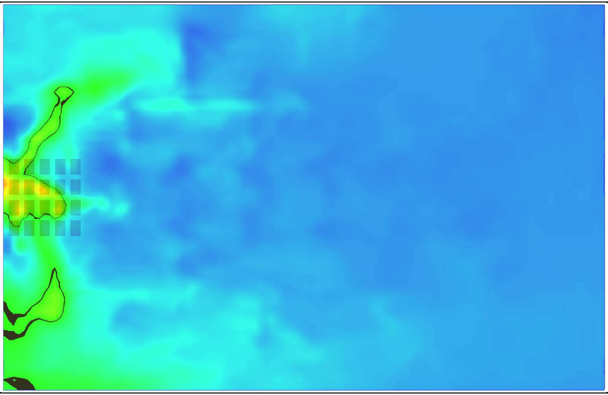
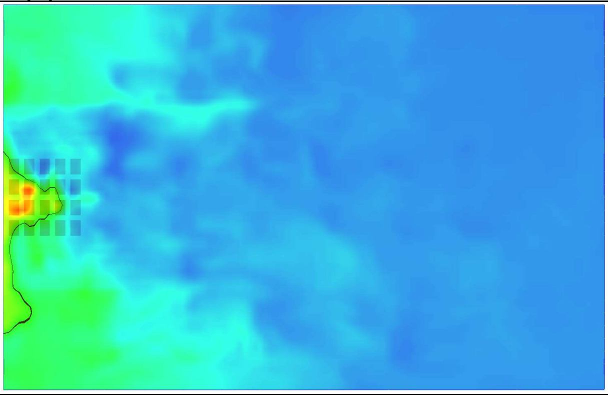

(e) Plan view 1m under the roof at 29 minutes

(g) Plan view 1m under the roof at 30 minutes

Figure 55: Temperature fields under the roof

Figure 56 shows the gas temperatures calculated at 1m under the roof directly above the ignition position and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), close or far away from the fire source (as indicated in Figure 57). The highest gas temperatures are reached at the level of thermocouples that are the closest to the fire source, namely Tf and T4, where a maximum temperature of 850°C is obtained after 30 minutes. It can be underlined that the temperature rise is a little higher at the wall level (T4), due to a deflection of flames towards the wall. The temperatures are significantly lower moving away from the fire source (thermocouples T1 to T3 and T5), these not exceeding 400°C throughout the fire.

Basing on a critical temperature of 650°C for steel members, it should be noted that the failure of the more heated steel members could happen in this fire scenario, without leading to the collapse of the entire structure.

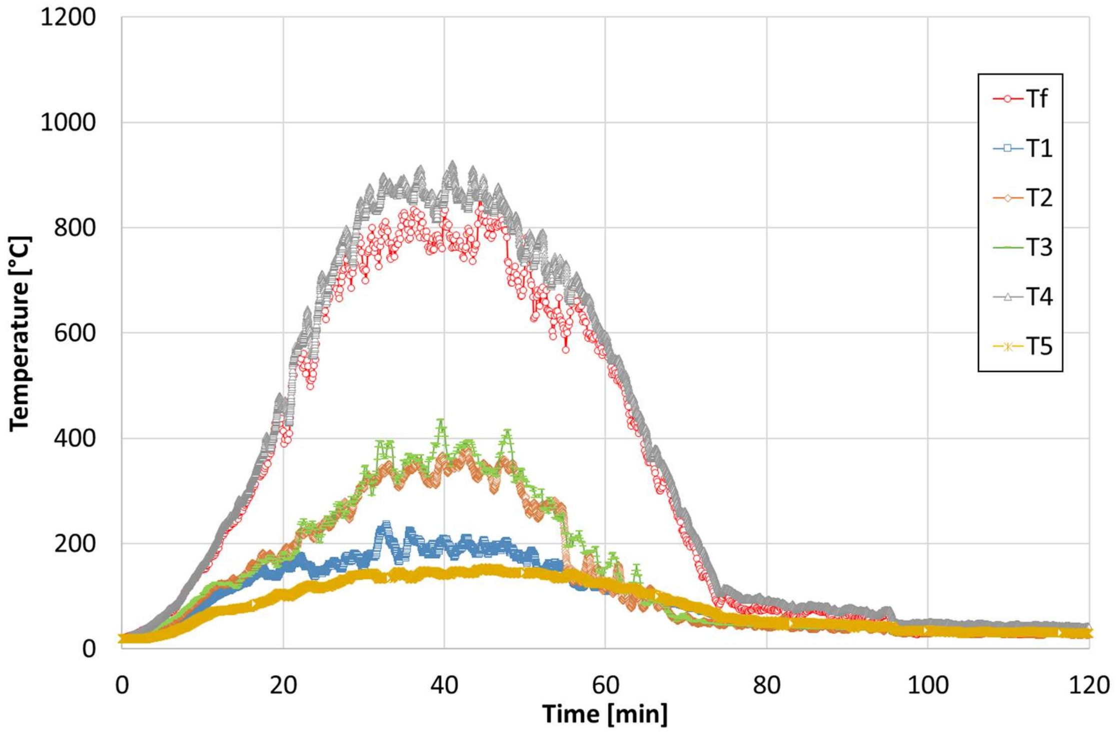


Figure 56: Gas temperature at different locations under the roof

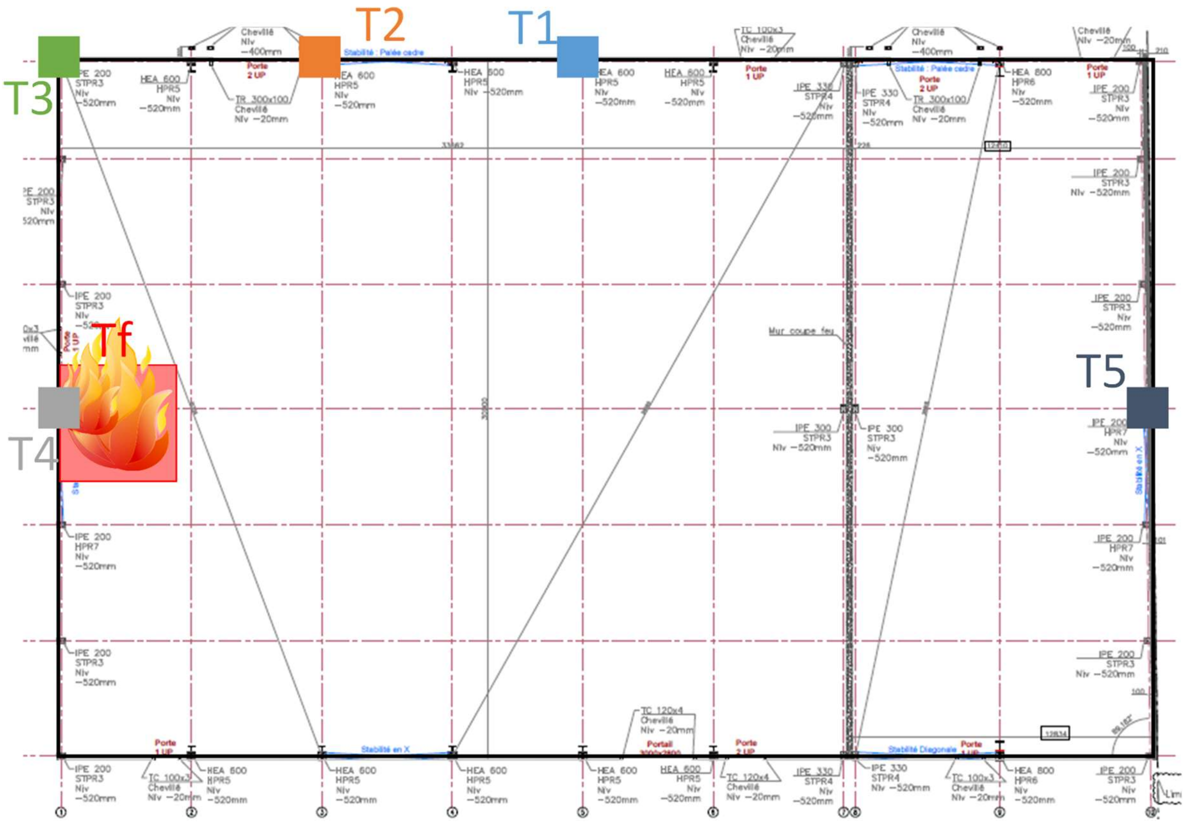


Figure 57: Temperature measurement point locations

Gas temperatures calculated at different wall heights nearest the fire source, at the same location as thermocouple T4 (near the fire ignition) are shown in Figure 58. It can be noted that gas temperatures increase uniformely along the height, in spite of small differences after 27 minutes (during the plateau) where temperatures ranging from 700 to 800°C are obtained.

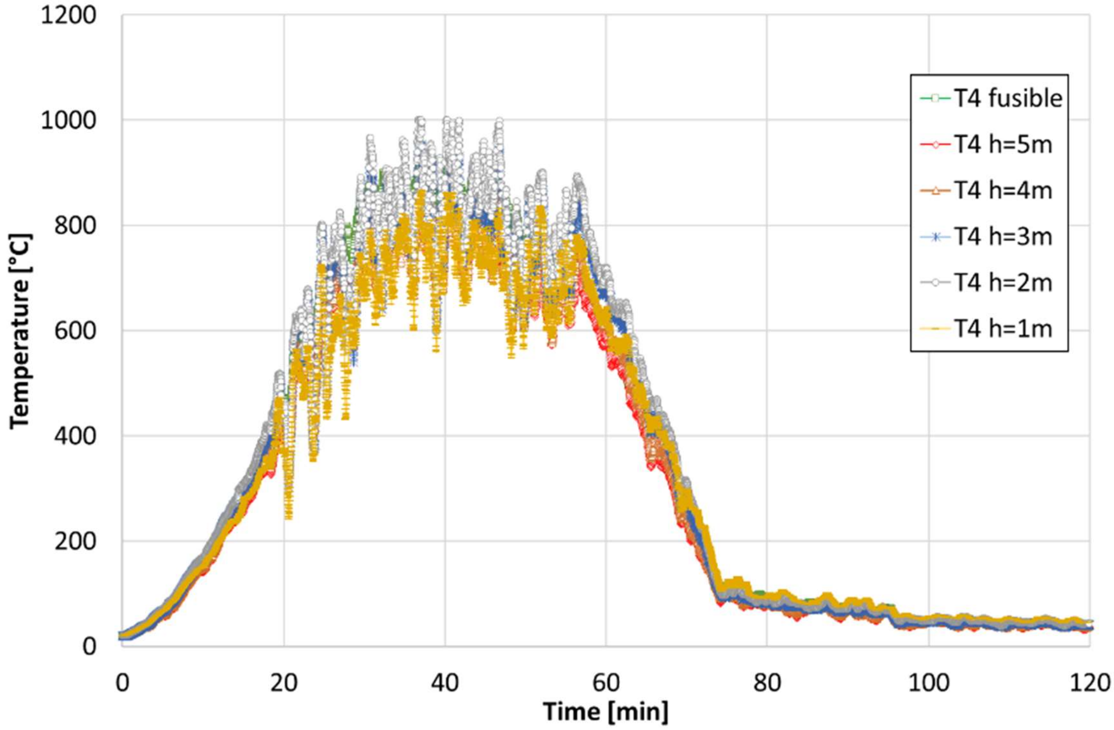
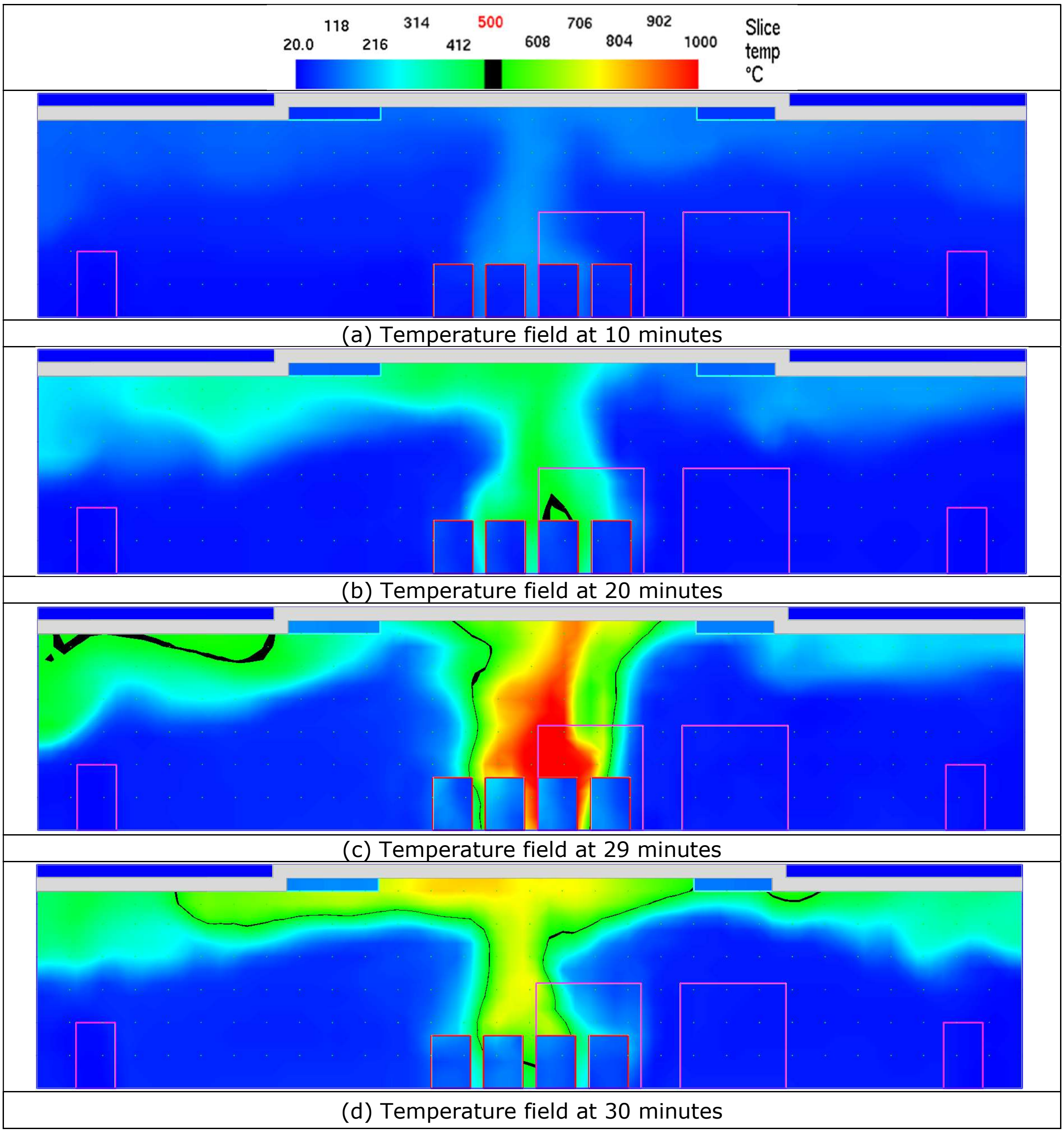


Figure 58: Gas temperatures versus time along the wall height at the location of thermocouple T4



(a) Temperature field at 10 minutes

(b) Temperature field at 20 minutes

(c) Temperature field at 29 minutes

(d) Temperature field at 30 minutes

Figure 59: Temperature fields in the plan of the steel portal frame the nearest of the fire source

4.4 Scenario W.4.3

This scenario concerns a 12000m² warehouse with a racking storage system. The source of fire is situated in the middle of a central double row rack.

The calculated HRR is shown in Figure 60. The plan views in Figure 61 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. It can be noted that the central position of the ignition leads to a fast fire growth. Due to the huge size of the warehouse, after 60 minutes, a large part of the pallets is still not burning (see Figure 61j), although gas temperature under the roof reaches 1000°C in all the left zone of the building where the fire is ignited. Nevertheless, the fire spreading is at this time very fast.

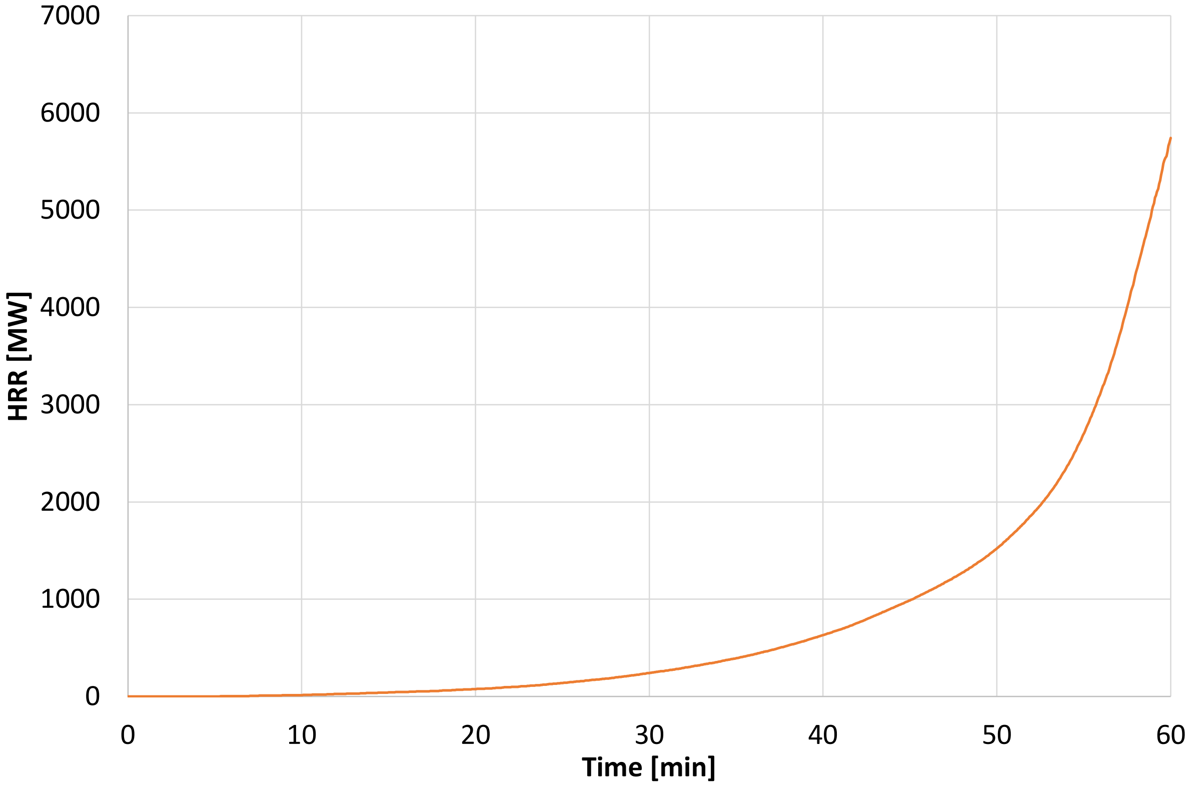
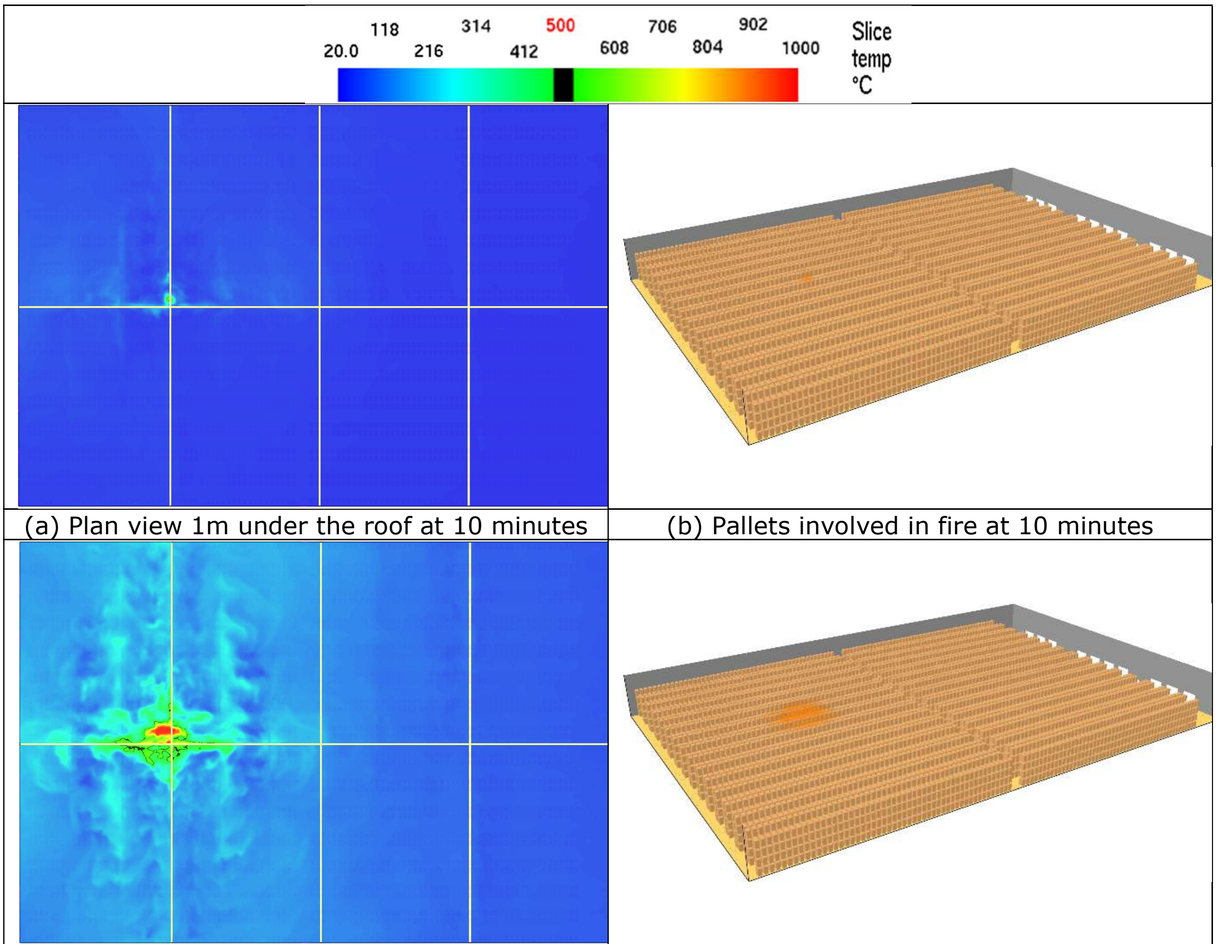


Figure 60: HRR calculated for the scenario W.4.3

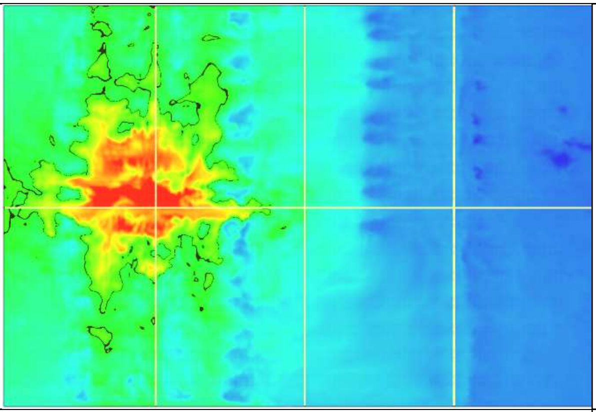


(a) Plan view 1m under the roof at 10 minutes

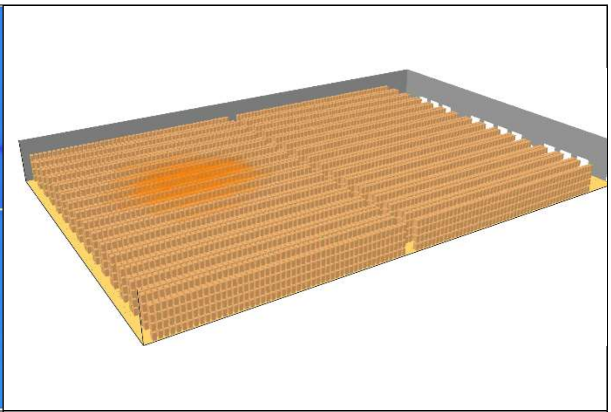
(b) Pallets involved in fire at 10 minutes

(c) Plan view 1m under the roof at 30 minutes

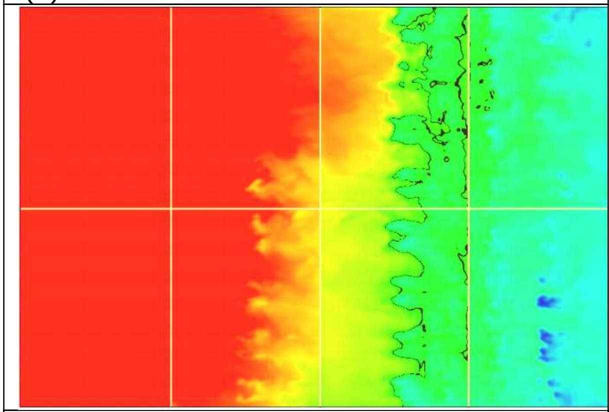
(d) Pallets involved in fire at 30 minutes



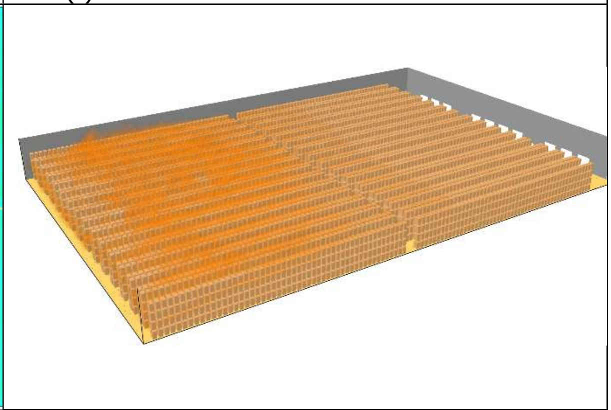
(e) Plan view 1m under the roof at 45 minutes



(f) Pallets involved in fire at 45 minutes



(i) Plan view 1m under the roof at 60 minutes



(j) Pallets involved in fire at 60 minutes

Figure 61: Temperature fields under the roof and surfaces involved in the fire

Figure 62 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), close or far away from the fire source (as indicated in Figure 63). Despite the fast fire growth, the distance between the fire ignition zone and the walls is too important to observe a fast temperature increase at the walls level (thermocouples T1 to T5). It is possible to see that the gas temperature above the fire source (thermocouple Tf) reaches 600°C and 100°C after 10 and 15 minutes respectively, while the other measurement points still give a gas temperature lower than 200°C. The gas temperature at thermocouples T1 to T5 reach 600°C after 48 minutes, and the highest temperature of 1000°C after 55 minutes.

Basing on a critical temperature of 650°C for steel members, it should be noted that a global structural collapse will inevitably happen with this fire scenario.

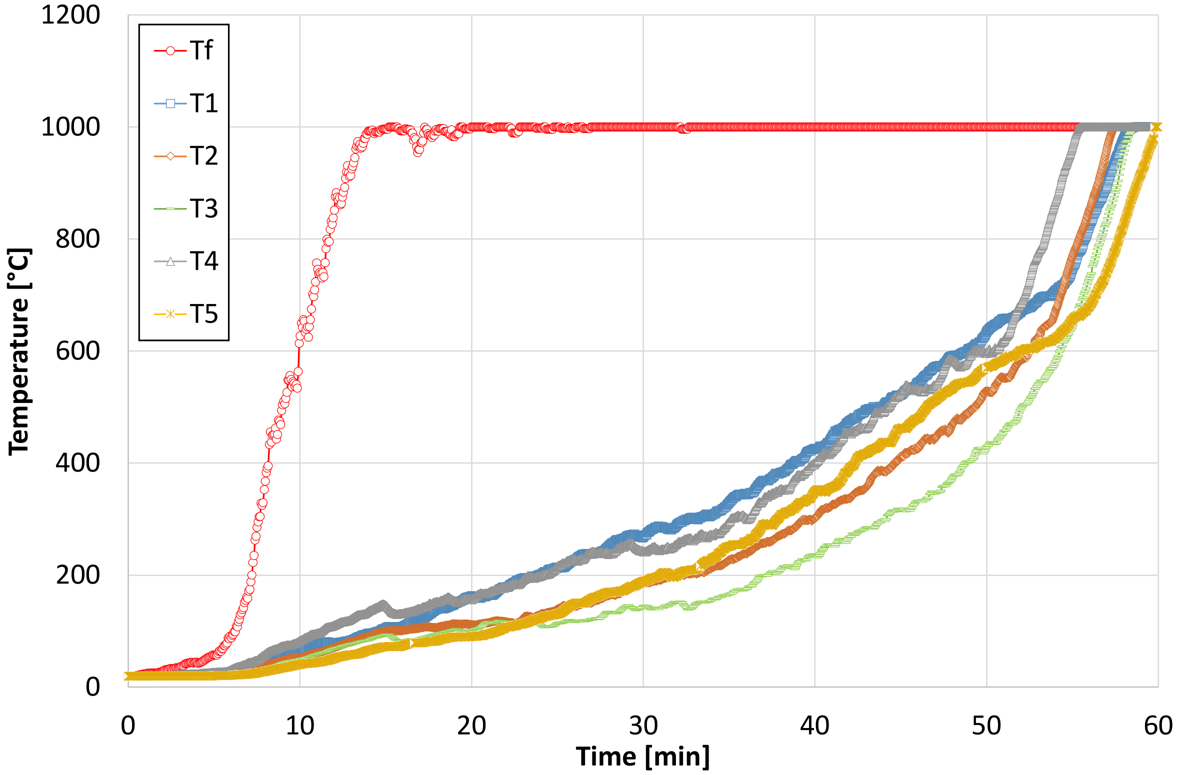


Figure 62: Gas temperature at different locations under the roof

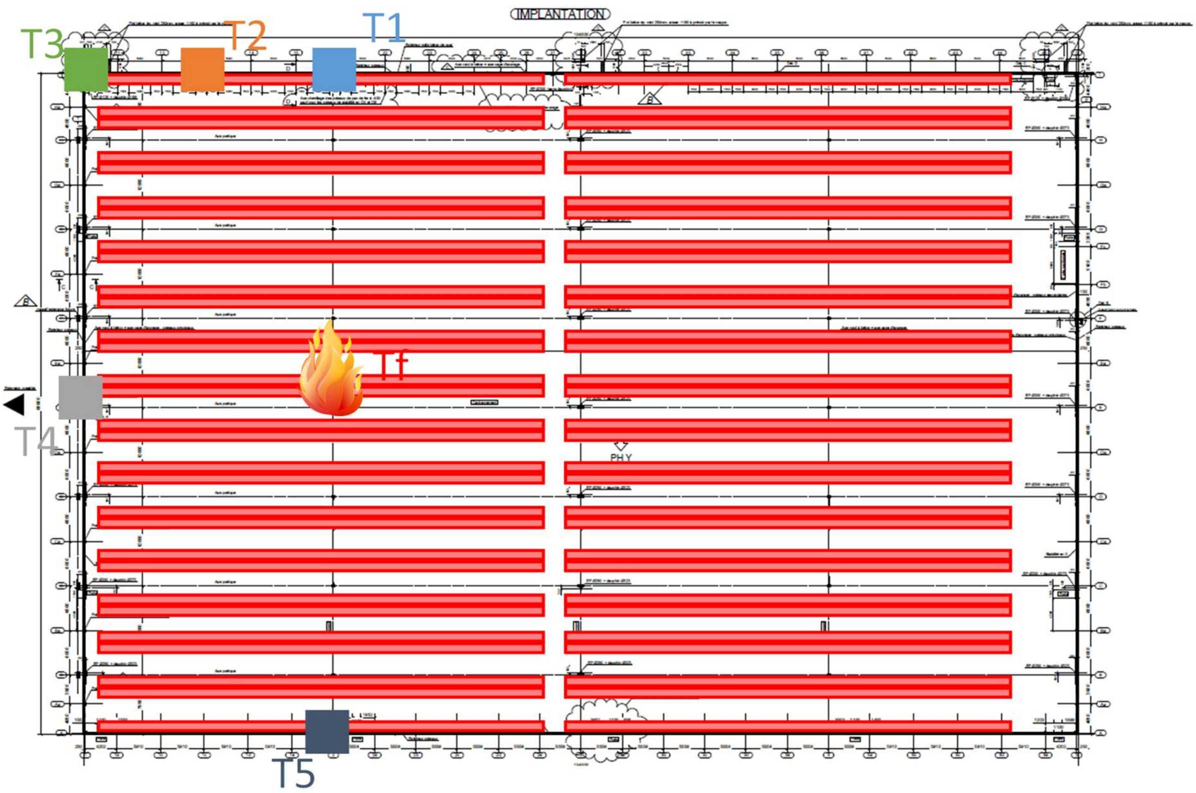
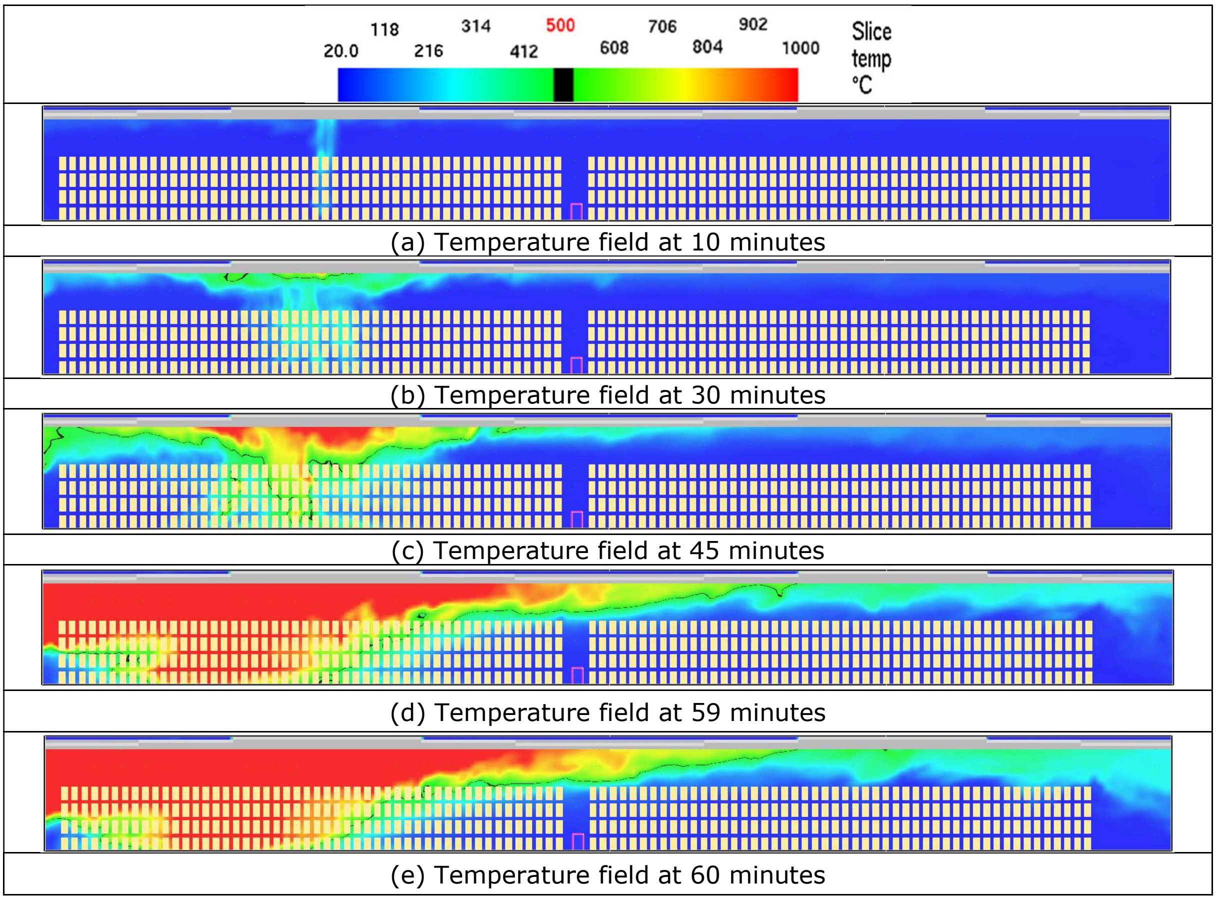


Figure 63: Temperature measurement point locations



(a) Temperature field at 10 minutes

(b) Temperature field at 30 minutes

(c) Temperature field at 45 minutes

(d) Temperature field at 59 minutes

(e) Temperature field at 60 minutes

Figure 64: Temperature fields in the plan of the steel portal frame the nearest of the fire source

5 CONCLUSIONS

Focusing on natural fires, the gas temperatures within the reference steel-framed single-storey buildings defined in deliverable D1.1 of the project were simulated using the FDS tool. Several fire scenarios were defined according to the different occupancies of buildings targeted by the project, namely industrial, storage or commercial activities. In particular, the different fire scenarios selected involve fires igniting either in palletized racking systems, shelf systems or in bulks storage, leading to localised or fully engulfed fires.

Simulation results showed that three main parameters have a significant effect on the highest temperatures reached inside the investigated buildings: the location of the fire source, the building geometry and the combustible materials (type, amount and fire design scenario).

Simulation results showed that highest temperatures at location where fusible systems could be present are obtained earliest for scenarios with a fire starting close to a wall. Indeed, combustible materials involved in ignition have a direct impact on nearby elements, which are partially engulfed in flames. This phenomenon is accentuated by the presence of the wall, which causes a depression that deflects the flame towards it.

With increasing distance from the fire source, gas temperatures decrease also. A fire starting far away from the building walls leads to an important increase of gas temperatures in zones near the fire source, while the gas temperatures in the vicinity of the walls increase with some time delay. Thus, an ignition far away from the building walls may cause a structural collapse, before the fusible systems break.

Building dimensions have a double impact on the results. The larger the building is, the greater the volume to be heated is. Thus, gas temperatures inside large buildings are lower when the fuel load is not important. In addition, it causes a longer delay in temperature rise between the different walls of the building. These phenomena may cause a structural collapse, before the fusible systems melt.

Finally, important differences can be observed between combustible materials. For warehouse scenarios, almost the entire roof area reaches high temperatures of around 1000°C during a long time period. These temperatures are important enough to cause the structural collapse and fusible systems to break. For supermarkets, fuel load is lower than for warehouses and the height between the top of the shelves and the roof is more important. Thus, highest temperatures are reached near the fire zone, which can lead to a localised collapse of the structure. Concerning industrial buildings, temperatures under roof are important enough to cause the fusible systems to break, but are unlikely to lead to a structural collapse.

It should be noted that the simulation results will be used in the Work Package 3 of the project dedicated to the study of unprotected steel structures associated to fire walls with fusible systems in case of fire. Only the real fire scenarios deemed to be the most representative will be selected. The selection will be done keeping in mind that one of the most unfavourable situation for a fire wall with fusible systems is that of a fire leading to a structural collapse, and at the same time to a limited heating of fusible systems. In a fire situation, fusible links have to allow the wall to be disconnected from the structure affected by fire without endangering the separating function of the wall, which must remain fixed to the steel structure on the other side of the wall and therefore not exposed to fire. However, unprotected steel-framed structures exposed to fire conditions usually exhibit two successive steps of structural behaviour. The first step is due to the thermal expansion of the heated members, which results in pushing forces on the neighbouring structures. Then, as steel increases in temperature, it loses its resistance and stiffness and the heated steel structure starts to fall inwards, leading to tensile forces on the neighbouring structures. Thus, in fire situation, it is necessary to ensure that fusible links located on both sides of the wall will resist the pushing phase and fusible links located on the fire-exposed side will fail first for the tensile phase. Moreover, in case where the steel roof structure is supported by the fire wall (case of a load-bearing wall solution), It is also important to avoid any sudden collapse that could endanger people (occupants or fire-fighters) being present in the building due to an atmosphere still tenable near the fire wall. The investigated fusible link solutions includes aluminium bolts acting as the fusible component. Consequently, since aluminium show a noticeable decrease in strength from 150°C (by losing at least 20% of its resistance), they should well-behaved in tensile phase whatever the fire situation.

The assessment that the investigated fusible link solutions are adequately designed to meet the above-mentioned requirements will be mainly done with help of global 3D modelling intended to be developed in the scope of the task 3.6 to investigate the mechanical response of unprotected steel structures associated with fire walls using "fusible" links under real fire conditions.

6 REFERENCES

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APPPENDIX A. RESULTS OF CFD SIMULATIONS

A.1. Scenario W.1.2

This scenario concerns a 1400m² warehouse with a racking storage system. The source of fire is placed at the end of the central double-row racks near one of the shorter building wall.

The calculated HRR is shown Figure 65. The plan views in Figure 66 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. It should be noted that the spreading dynamics is similar to that obtained in scenario W.1.1. However, the ignition in double-row racks leads to a fire growth slightly faster. The flashover starts at 17 minutes. As for the scenario W.1.1, this phenomenon is due to the short height between the top of the storage and the roof as well as the small free volume inside building. Indeed, hot gases, produced by the fire, quickly fill the free volume between the third racks level and the roof. At the same time, their temperature increasing, the pallets ignite one after the other. Then, most of pallets are ignited after 25 minutes. It should be noted that, although the openings area is important (9% of the roof surface), the natural smoke extraction flow is not enough to efficiently evacuate all the heat generated by the fire. After 67 minutes, the amount of fuels gradually decreases with the pallets combustion, until the total extinction of the fire at 76 min due to a lack of combustible.

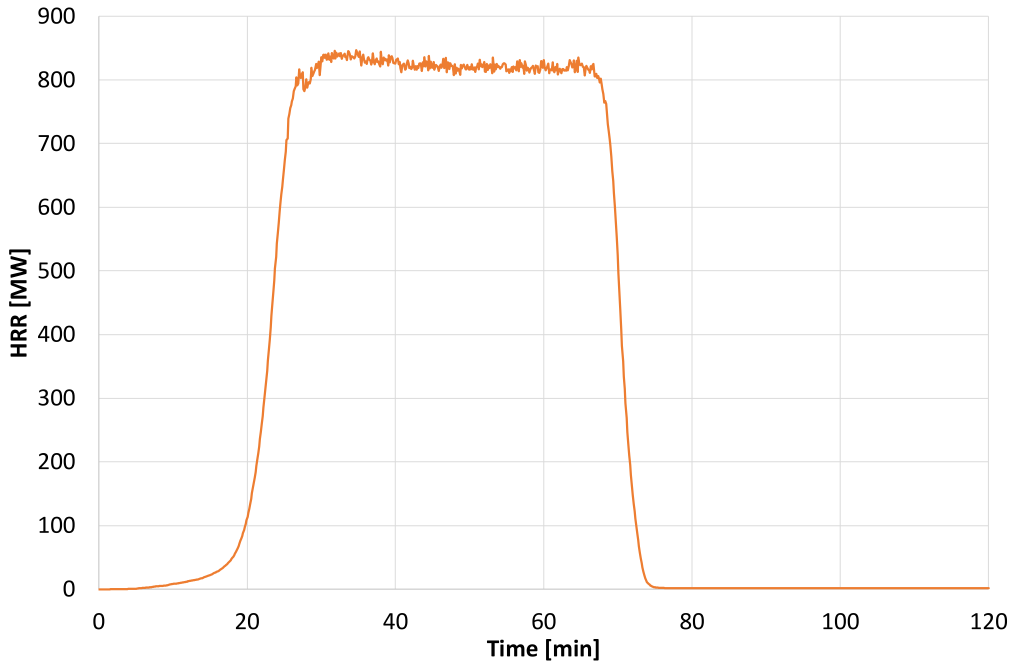
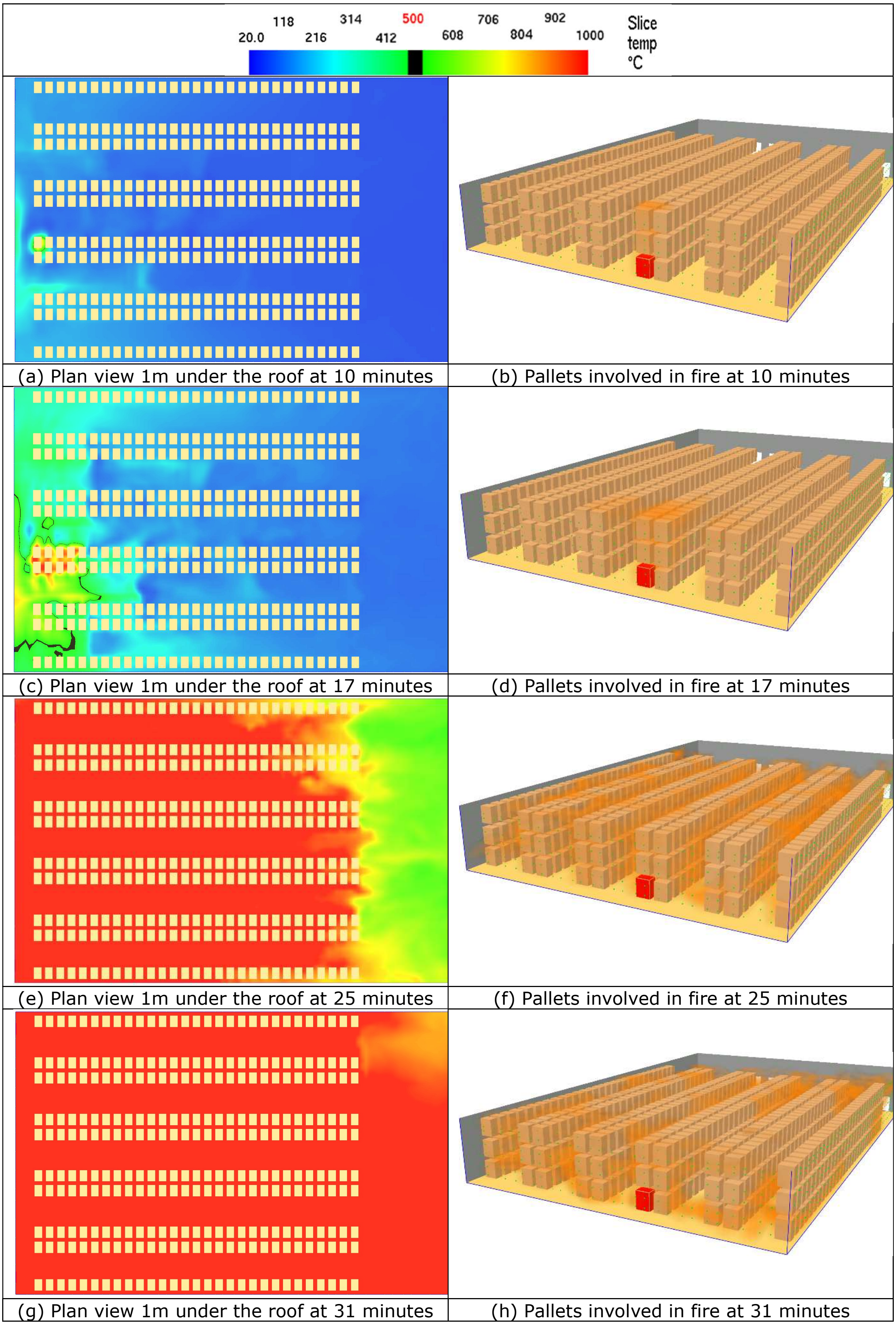


Figure 65: HRR calculated for the scenario W.1.2

Figure 67 shows the gas temperatures calculated at 1m under the roof directly above the fire ignition position and at different locations along the building walls (where "fusible" systems connecting fire walls could be present) ,close or far away from the fire source (as indicated in Figure 68). During the first twenty minutes, it can be noted that the gas temperatures near the fire source area are quickly increasing. The calculated gas temperature at thermocouple Tf and T4 reach 600°c at 10 and 17 min respectively, while the other measurement points give gas temperatures lower than 300°C at the same times. Then, the gas temperatures increase fast in all parts of the building with the spread of fire between the pallets. Thermocouple T5, at the opposite position of the fire source location reaches 600°C after 26 minutes. The highest gas temperature of 1000°C is reached first at thermocouple Tf after 18 minutes, then successively at other thermocouples. After 31 minutes, the hot gas layer is uniformely distributed in the whole building: across the building height and under the building roof. Then, gas temperatures starts to decay at 75 min as the fuel load is consumed.



(a) Plan view 1m under the roof at 10 minutes

(b) Pallets involved in fire at 10 minutes

(c) Plan view 1m under the roof at 17 minutes

(d) Pallets involved in fire at 17 minutes

(e) Plan view 1m under the roof at 25 minutes

(f) Pallets involved in fire at 25 minutes

(g) Plan view 1m under the roof at 31 minutes

(h) Pallets involved in fire at 31 minutes

Figure 66: Temperature fields under the roof and surfaces involved in the fire

Figure 67 shows the gas temperatures calculated at 1m under the roof directly above the fire ignition position and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), close or far away from the fire source (as indicated in Figure 68). During the first twenty minutes, it can be noted that the gas temperatures near the fire source area are quickly increasing. The calculated gas temperature at thermocouple Tf and T4 reach 600°c at 10 and 17 min respectively, while the other measurement points give gas temperatures lower than 300°C at the same times. Then, the gas temperatures increase fast in all parts of the building with the spread of fire between the pallets. Thermocouple T5, at the opposite position of the fire source location, reaches 600°C after 26 minutes. The highest gas temperature of 1000°C is reached first at thermocouple Tf after 18 minutes, then successively at other thermocouples. After 31 minutes, the hot gas layer is uniformely distributed in the whole building: across the building height and under the building roof. Then, gas temperatures start to decay at 75 min as the fuel load is consumed.

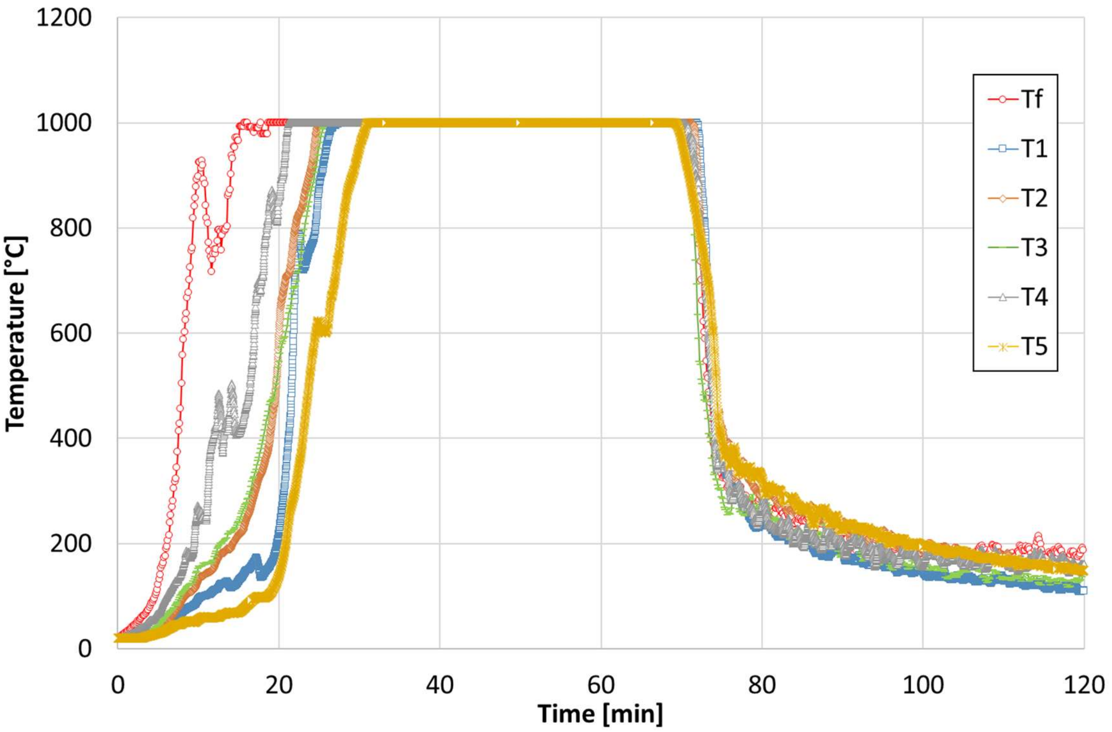


Figure 67: Gas temperature at different locations under the roof

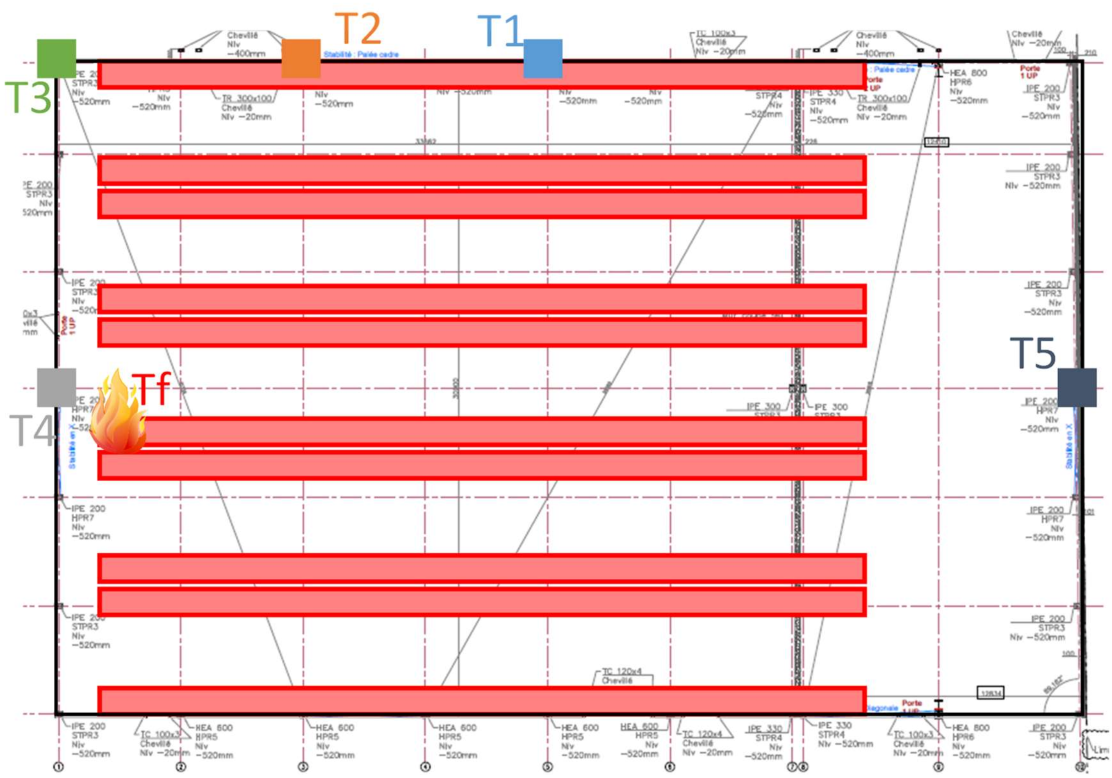


Figure 68: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple T4, are shown in Figure 69. It can be noted that temperatures reached along the height change significantly during the whole time of the fire. Although the gas temperature rapidly increases above 5 m height (with the development of a hot gas layer under the roof), it increases more slowly at the lower parts. At 19 minutes, the temperatures rise accelerates until gas temperatures reach everywhere the highest temperature of 1000°c, after flashover is reached (from 21 to 26 minutes approximately).

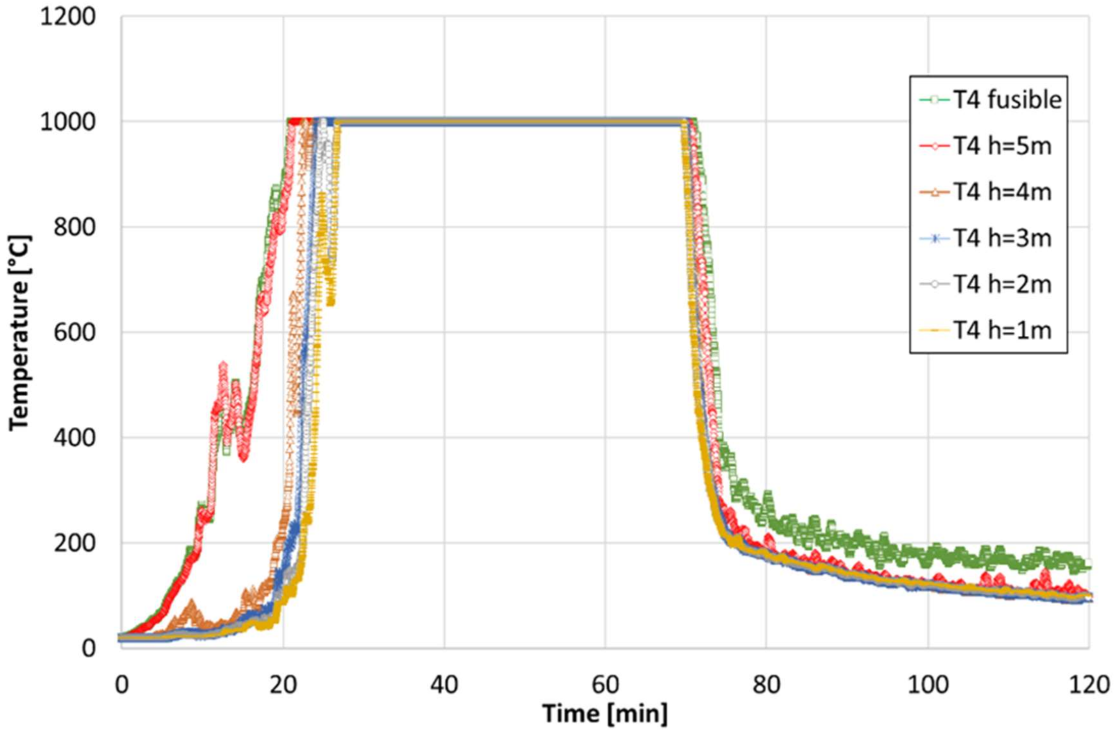
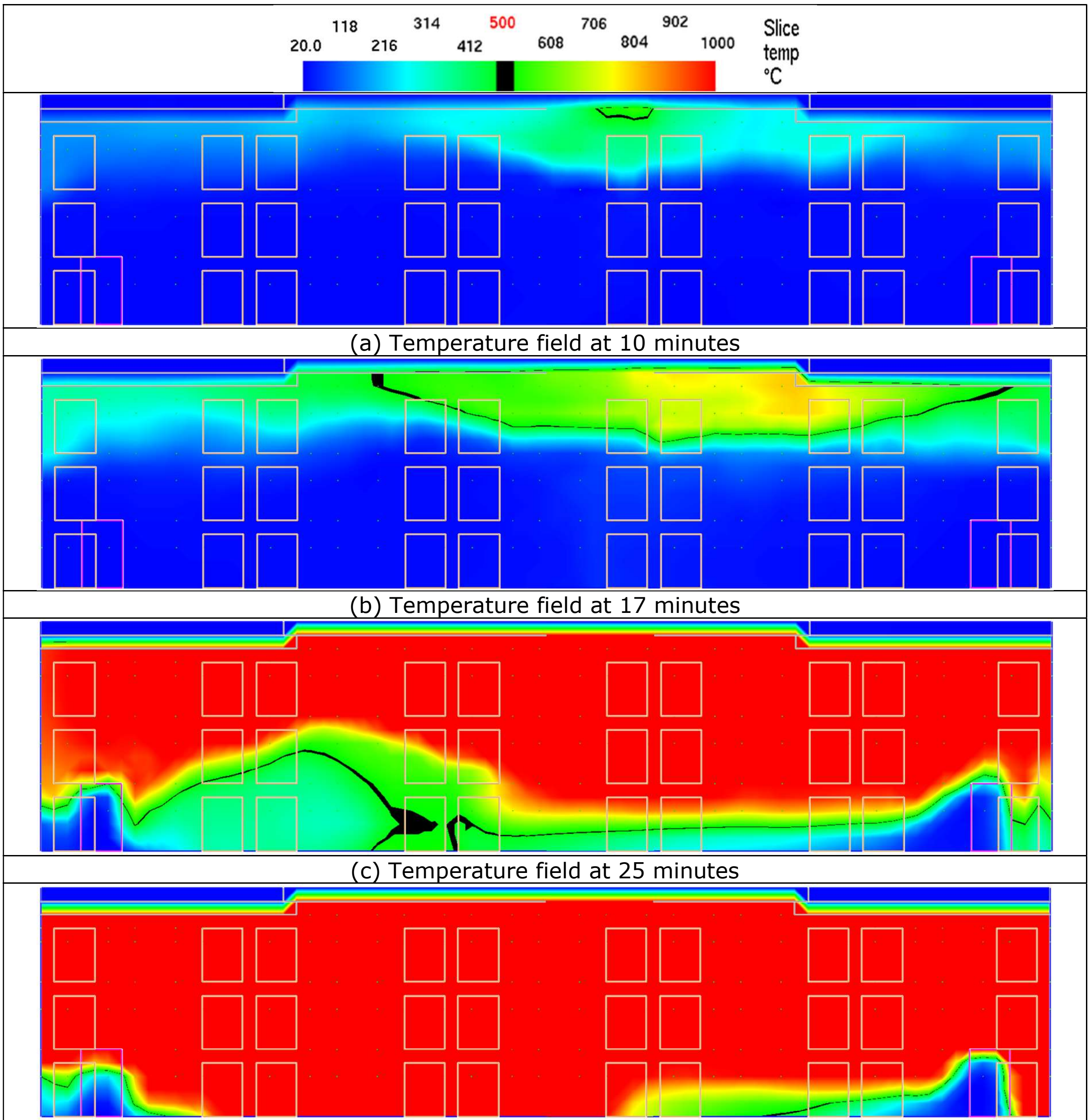


Figure 69: Gas temperatures versus time at different heights along the column at position T4



(a) Temperature field at 10 minutes

(b) Temperature field at 17 minutes

(c) Temperature field at 25 minutes

(d) Temperature field at 31 minutes

Figure 70: Temperature fields in the plan of the steel portal frame the nearest of the ignition position

A.2. Scenario W.1.3

This scenario concerns a 1400m² warehouse with a racking storage system. The source of fire is placed in the middle of the central double-row racks.

The calculated HRR is shown in Figure 71. The plan views in Figure 72 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. The central position of the ignition leads to a fast spreading of fire. This phenomenon can be explained by on one hand the short height between the top of the storage and the roof and on the other hand the small free volume of the building, as for the scenarios W.1.1 and W.1.2. The flashover starts here at 15 minutes (Figure 72c and Figure 72d). After 1 hour, the amount of fuels gradually decreases with the pallets combustion, until the total extinction of the fire at 76 min due to a lack of combustible.

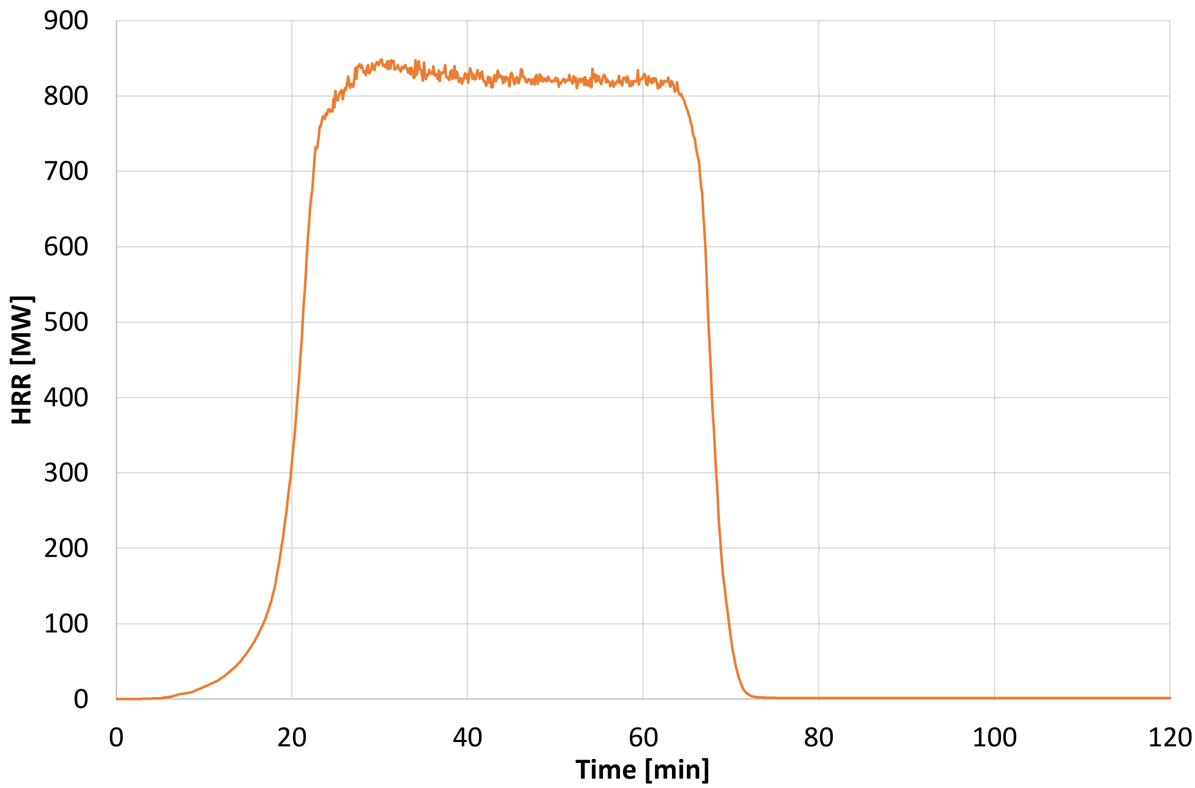
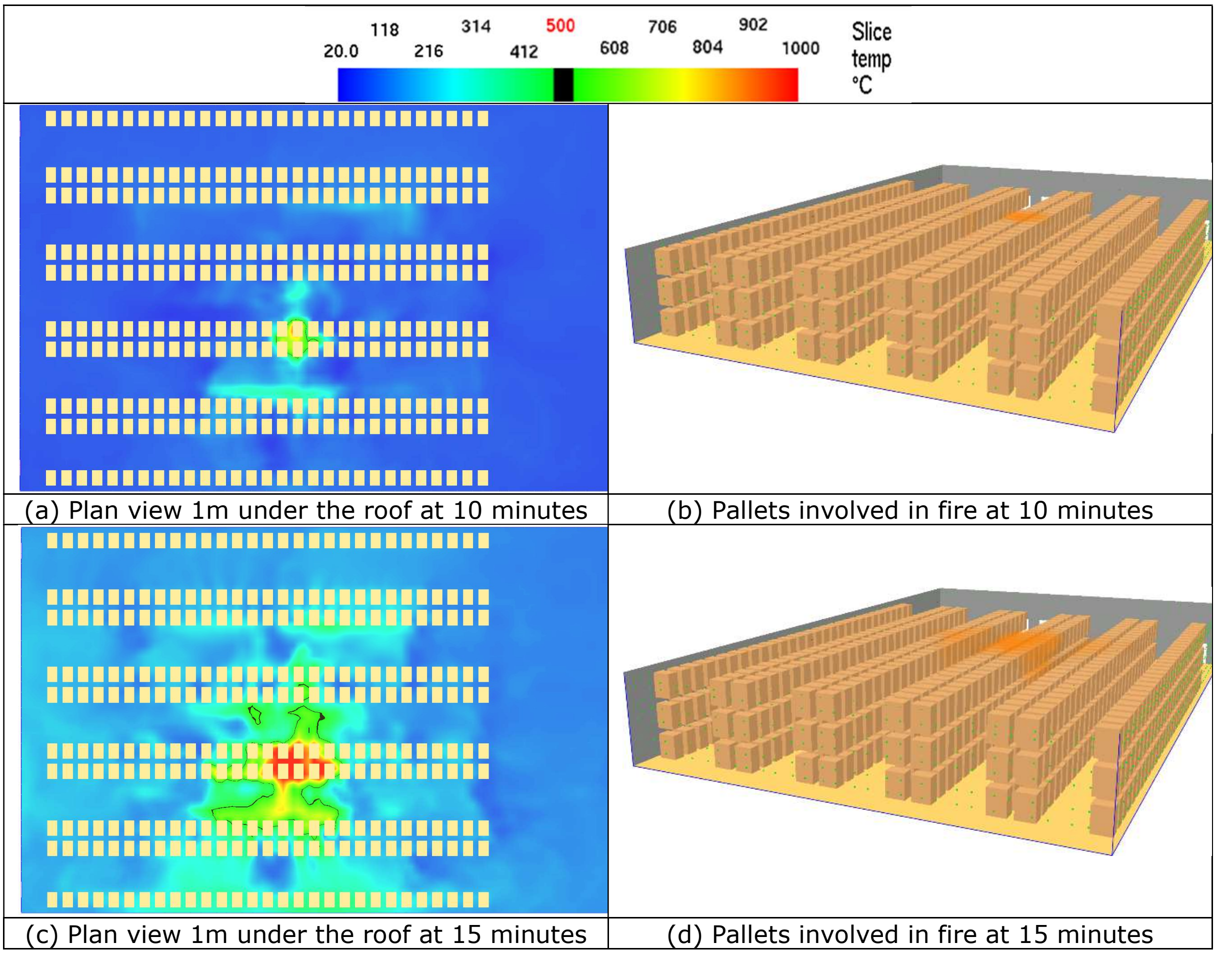


Figure 71: HRR calculated for the scenario W.1.3

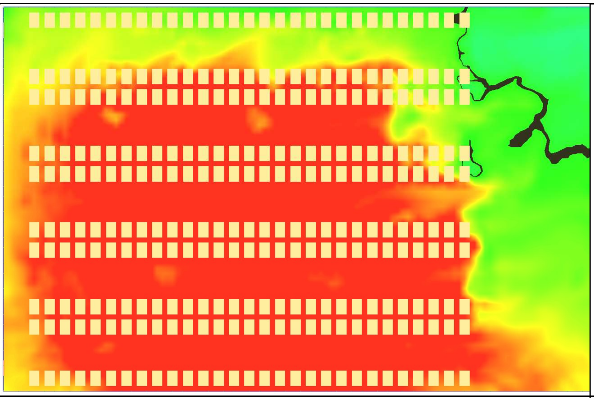


(a) Plan view 1m under the roof at 10 minutes

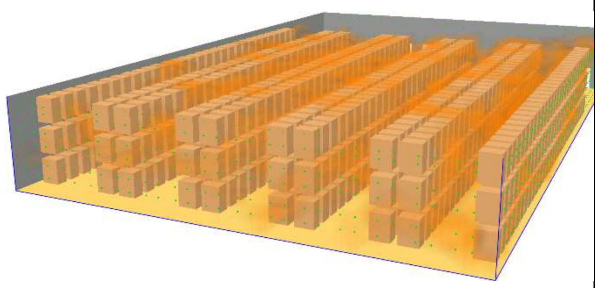
(b) Pallets involved in fire at 10 minutes

(c) Plan view 1m under the roof at 15 minutes

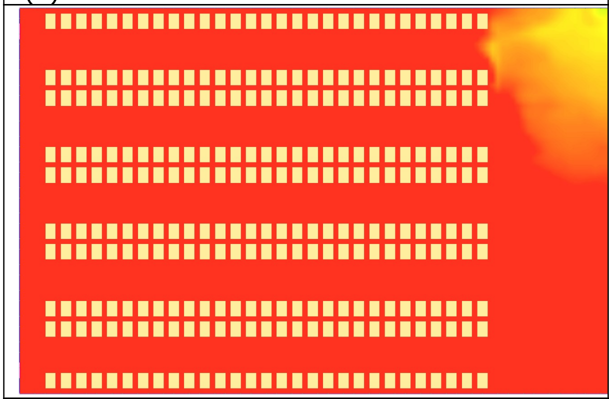
(d) Pallets involved in fire at 15 minutes



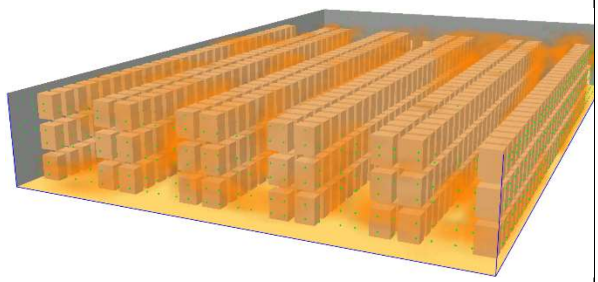
(e) Plan view 1m under the roof at 22 minutes



(f) Pallets involved in fire at 22 minutes



(g) Plan view 1m under the roof at 28 minutes



(h) Pallets involved in fire at 28 minutes

Figure 72: Temperature fields under the roof and surfaces involved in the fire

Figure 73 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present) close or far away from the fire source (as indicated in Figure 74). During the first 18 minutes, it can be noted that only the gas temperatures above the fire source area are quickly increasing. Indeed, the gas temperatures calculated at thermocouple Tf reach 600°c approximately at 7 min, while the other measurement points give gas temperatures lower than 100°C. Then, the gas temperatures increase progressively in other parts of the building with the spread of fire between the pallets. Thermocouples T1 to T5 show similar temperature rises, but delayed over time. At these thermocouples, a gas temperature over 600°C is reached after 20 minutes approximately. The highest gas temperature of 1000°C is observed first at thermocouples Tf after 17 minutes, and finally at the other thermocouples after 22 minutes. After 28 minutes, the hot gas layer is uniformely distributed in the whole building: across the building height and under the building roof. Then, gas temperatures start to decay at 76 min as the fuel load is consumed.

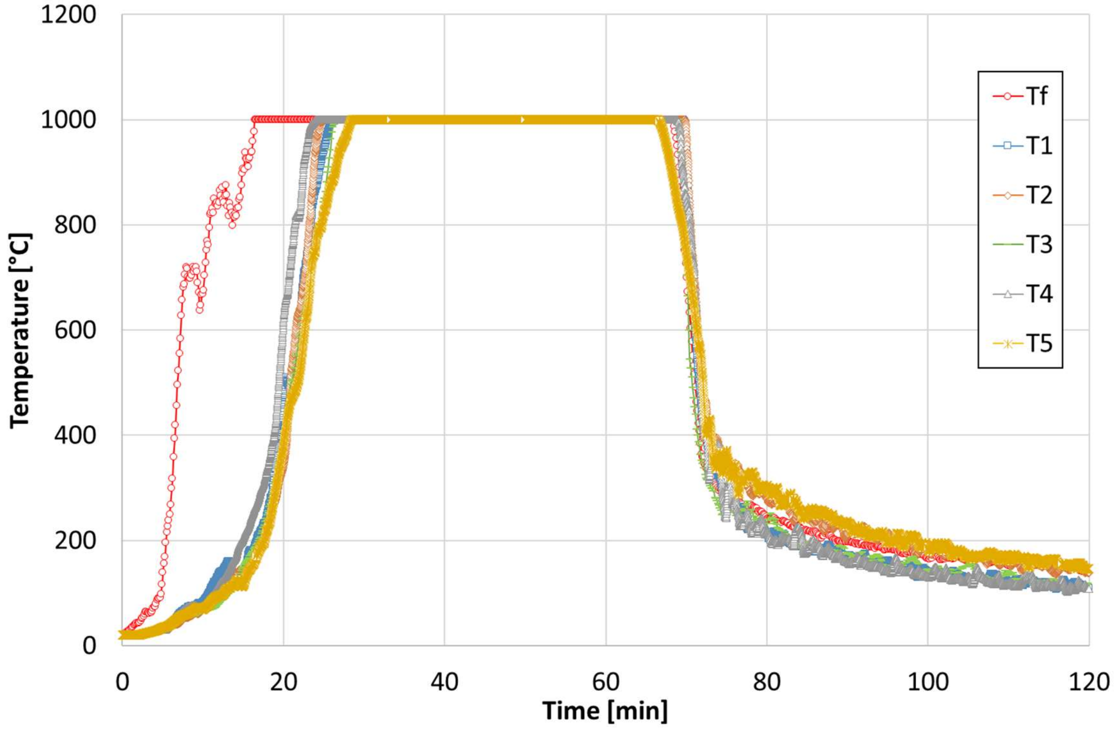


Figure 73: Gas temperature at different positions under the roof

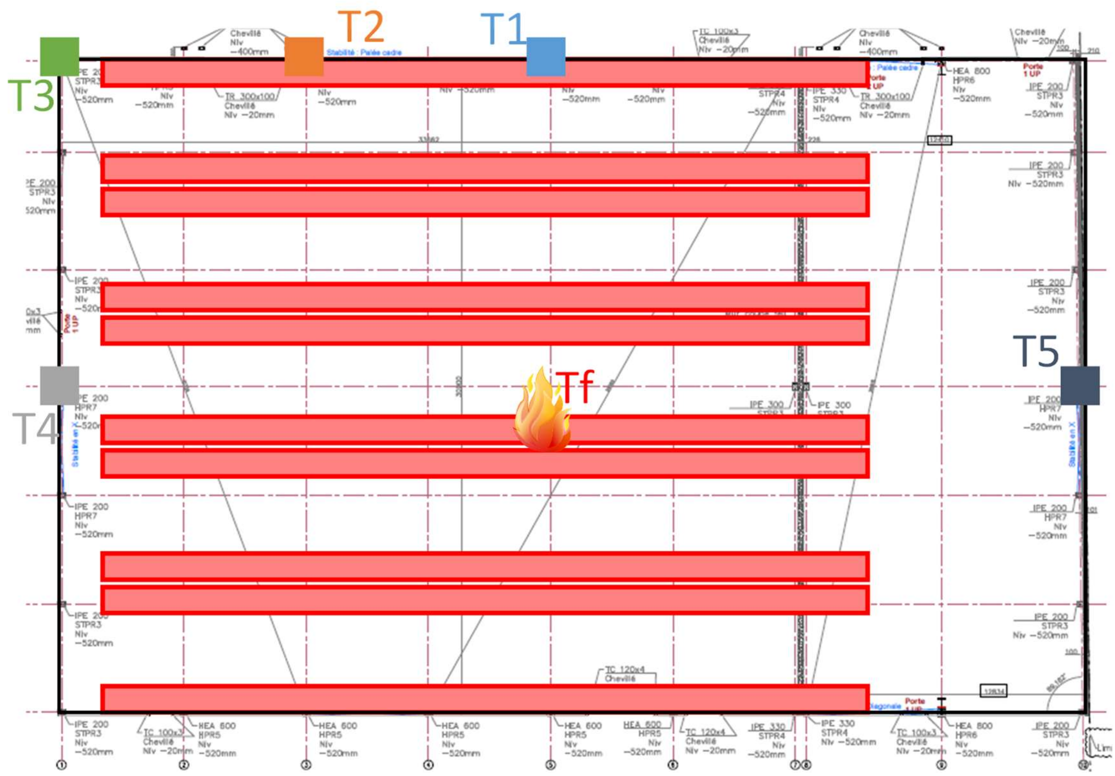
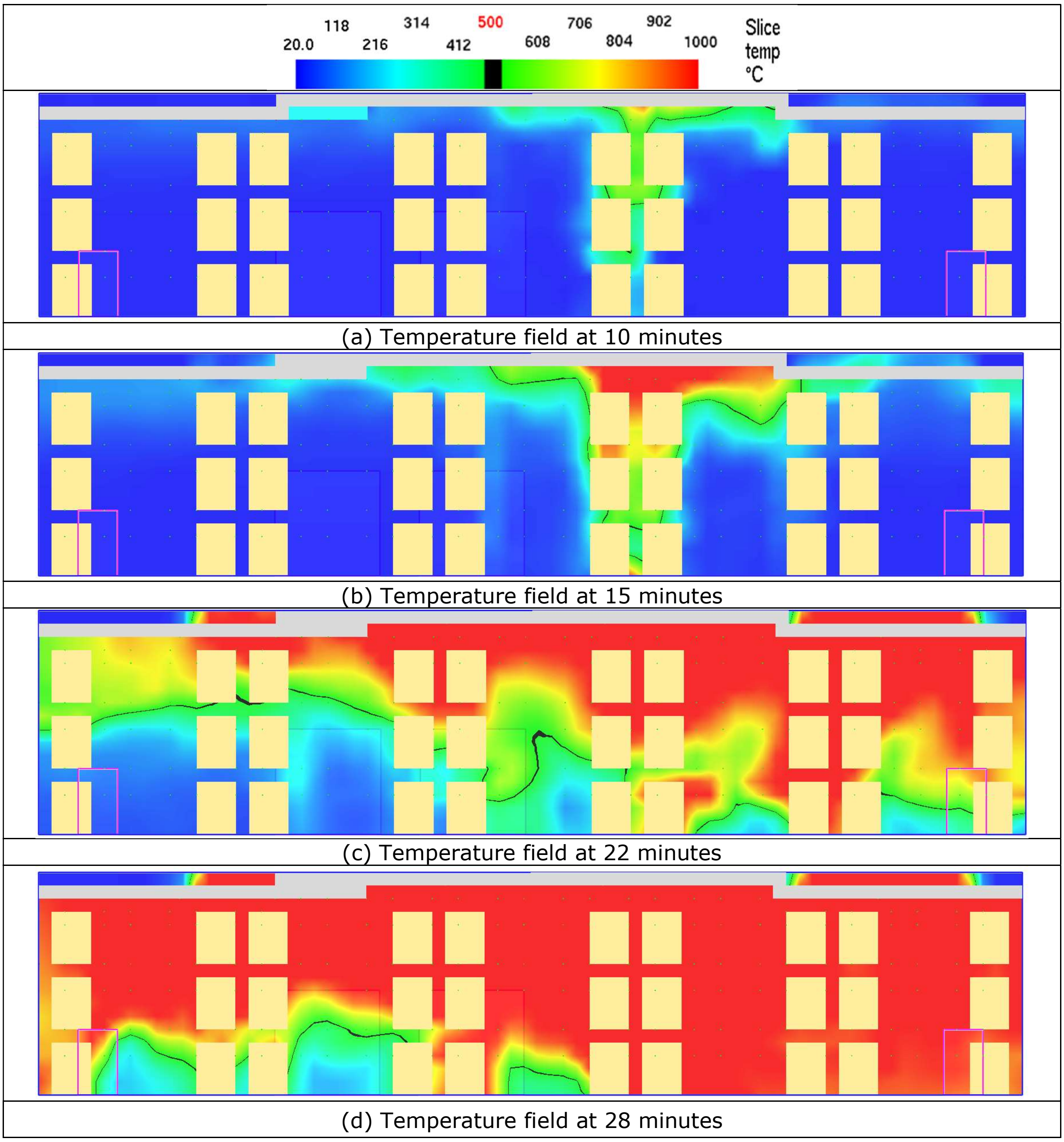


Figure 74: Temperature measurement point locations



(a) Temperature field at 10 minutes

(b) Temperature field at 15 minutes

(c) Temperature field at 22 minutes

(d) Temperature field at 28 minutes

Figure 75: Temperature fields in the plan of the steel portal frame the nearest of the fire source position

A.3. Scenario S.1.1

This scenario concerns a 1400m² supermarket with a shelf storage system. The source of fire is situated at the end of a central double-row shelves.

The calculated HRR is shown Figure 76. The plan views in Figure 77 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. In this scenario, the storage configuration does not allow to obtain a flashover. Indeed, the low quantity of fuel coupled with the important roof height leads to an important dilution. Moreover, the roof opening area is enough to allow an efficient evacuation of smokes and hot gases outside the building. The fire propagation occurs gradually and is driven by radiative heat fluxes. At 38 minutes, the five shelves that can be involved in fire are partially burning (Figure 77d). The low spreading rate does not allow a simultaneous combustion of all the fuel. First, fuels involved in the combustion stop burning before the end of the propagation (Figure 77h). Then, the peak HRR is obtained at 67 minutes. The amount of fuels gradually decreases with the combustion until the total extinction of the fire at 120 minutes.

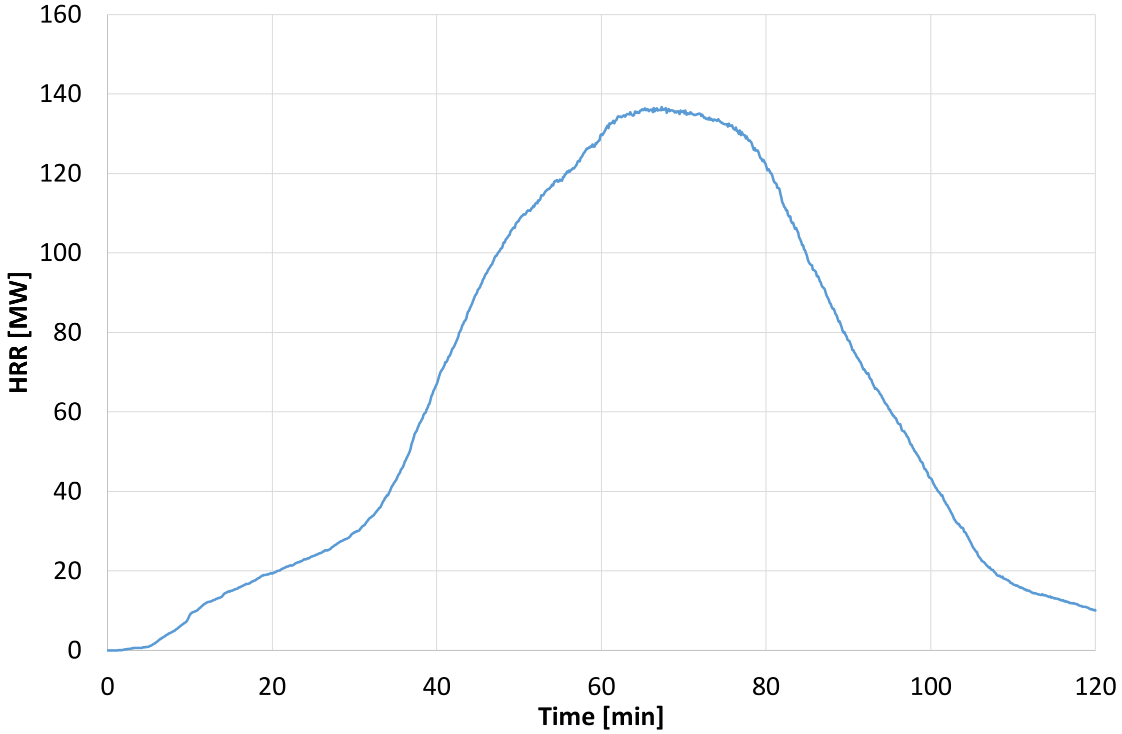
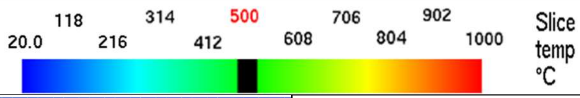
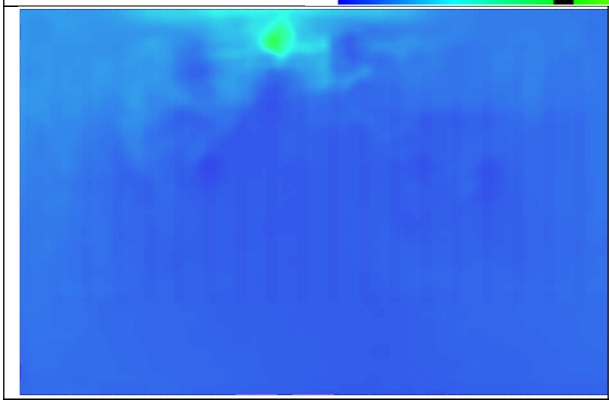
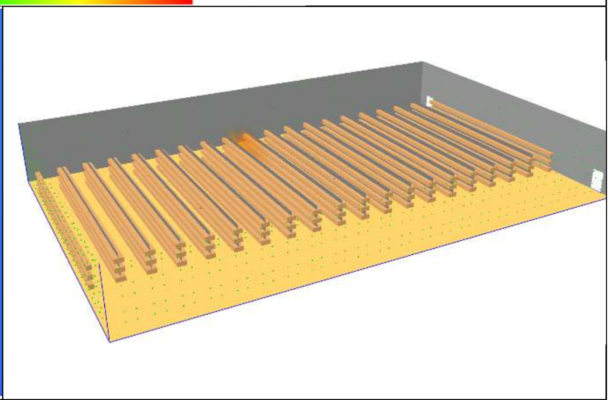


Figure 76: HRR calculated for the scenario S.1.1

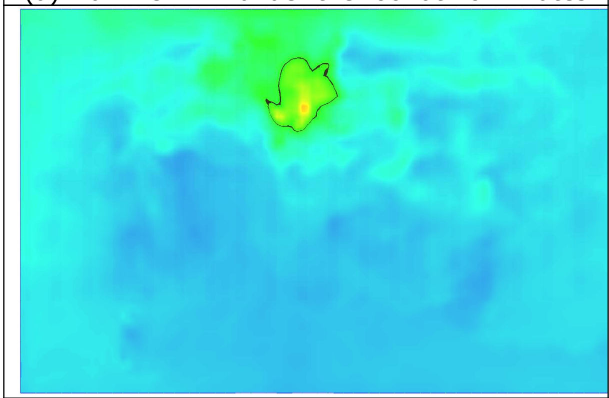




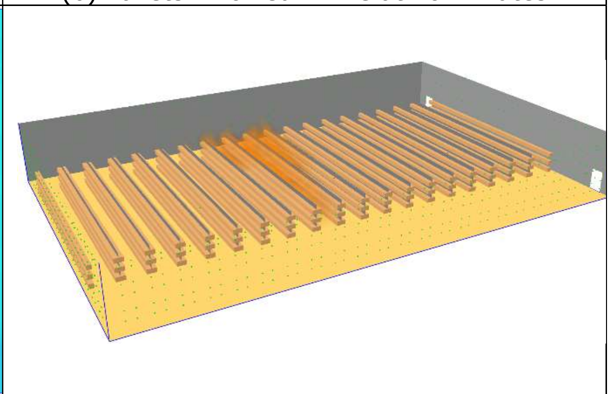
(a) Plan view 1m under the roof at 10 minutes



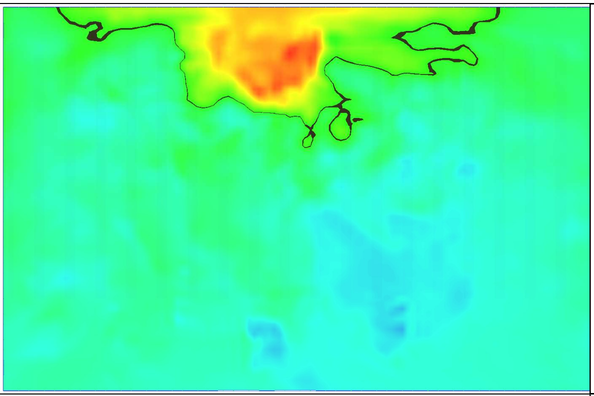
(b) Pallets involved in fire at 10 minutes



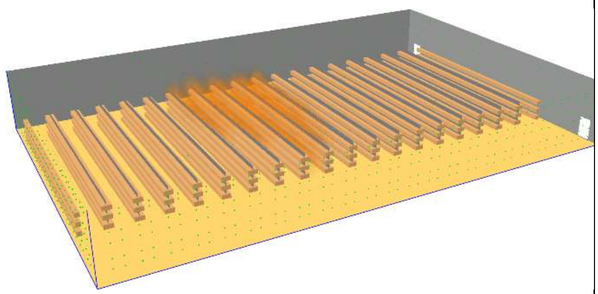
(c) Plan view 1m under the roof at 38 minutes



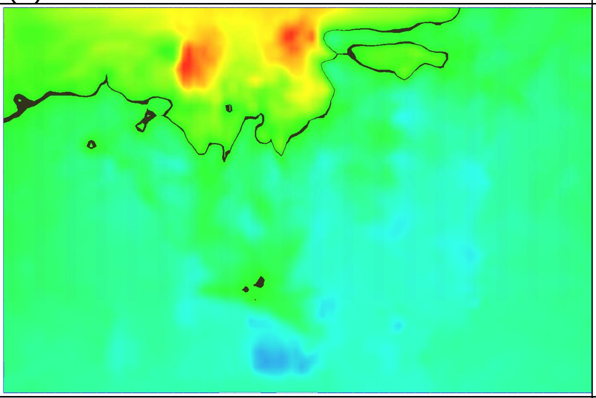
(d) Pallets involved in fire at 38 minutes



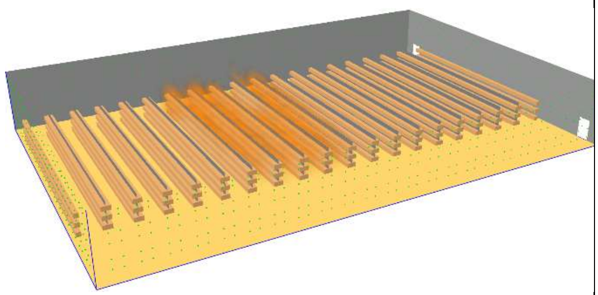
(e) Plan view 1m under the roof at 50 minutes



(f) Pallets involved in fire at 50 minutes



(g) Plan view 1m under the roof at 60 minutes



(h) Pallets involved in fire at 60 minutes

Figure 77: Temperature fields under the roof and surfaces involved in the fire

Figure 78 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 79). During the first 33 minutes of the combustion, all the temperatures under the roof are lower than 400°C. Only the thermocouples T1, T2 and T3 (near the ignition zone) show temperatures over 600°C after 38, 42 and 58 minutes, respectively. At 60 minutes, all the temperatures reach a plateau from 350 to 750°C according to the considered thermocouple. After 80 minutes, gas temperatures start to decay as the fuel load is consumed.

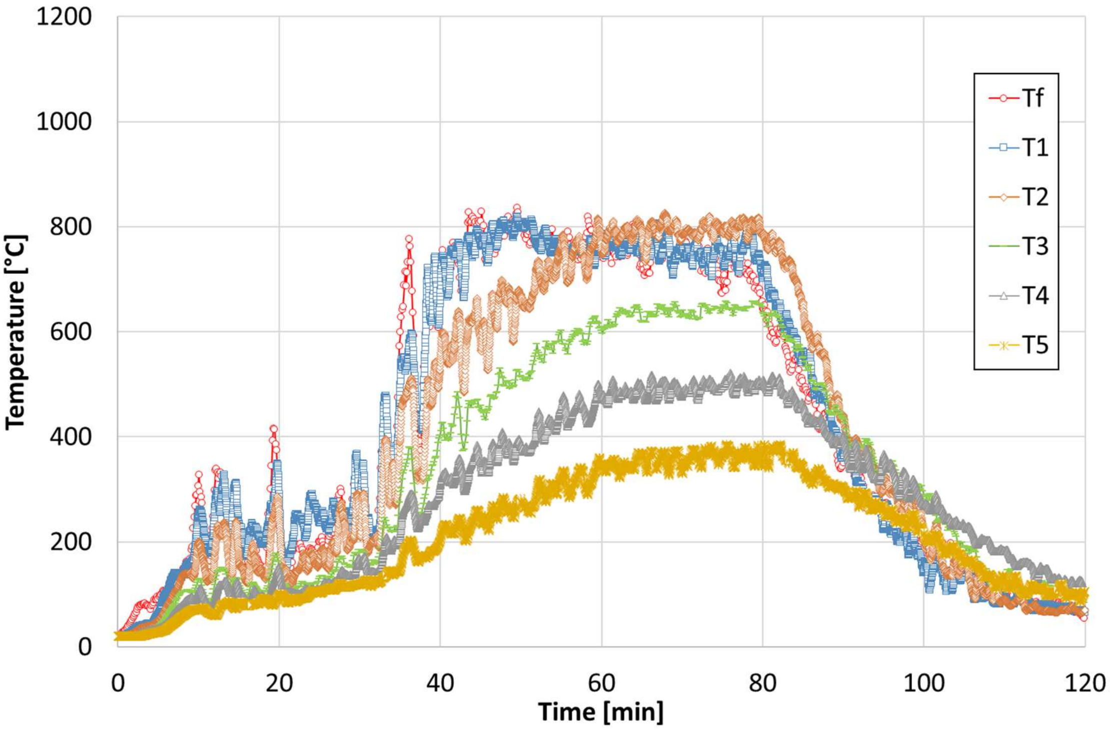


Figure 78: Gas temperature at different locations under the roof

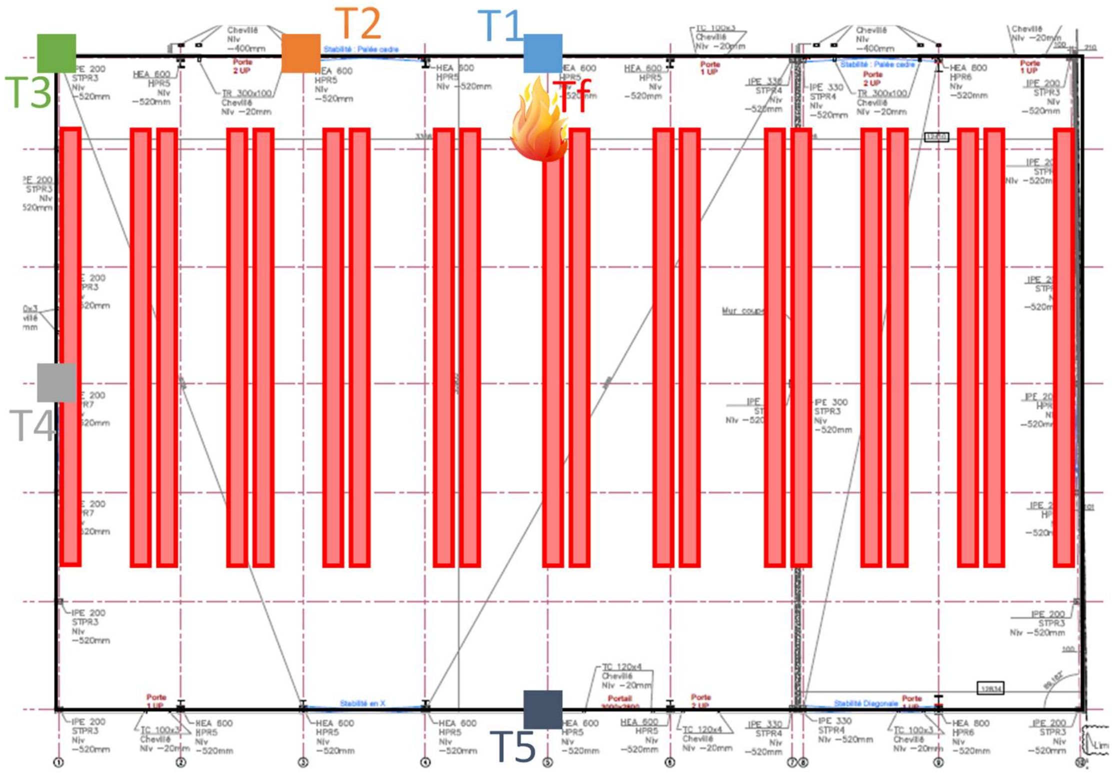


Figure 79: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple T1, are shown in Figure 80. It can be noted that gas temperatures over 4 m height are very close during the 40 first minutes of the fire. All the thermocouples over 2 m reach their maximum temperatures after 50 minutes. Although temperatures over 3m are over 700°C at this moment, the lower part of the column show temperatures under 500°C.

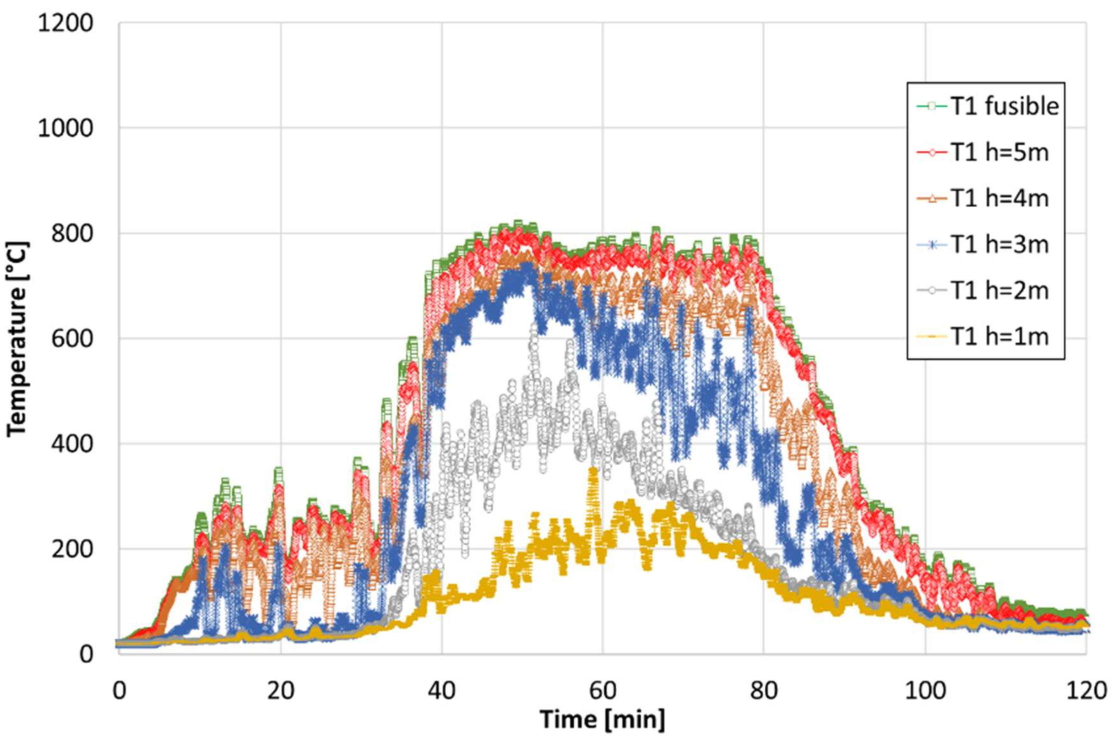
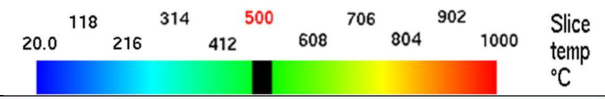
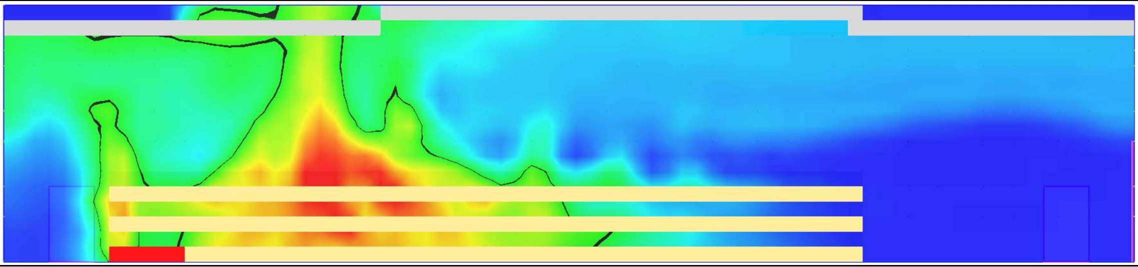


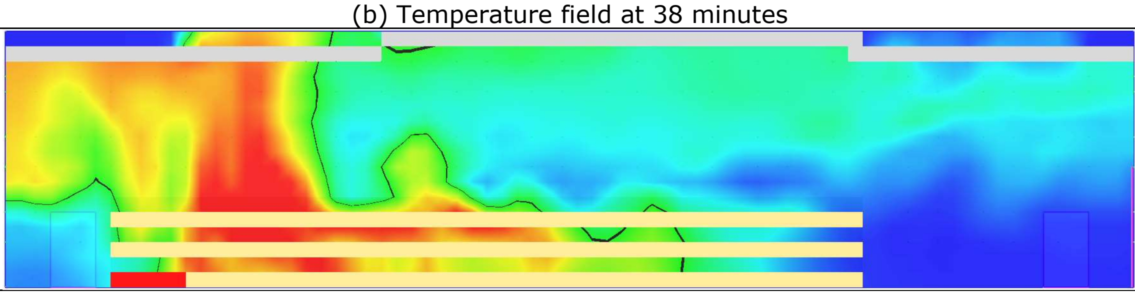
Figure 80: Gas temperatures versus time along the wall height at the location of thermocouple T1



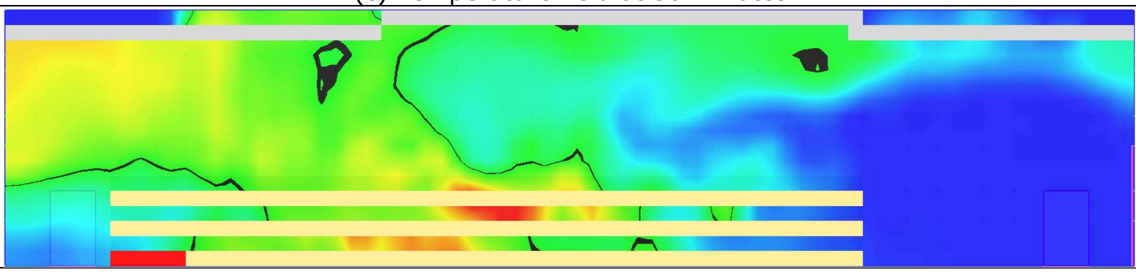
(a) Temperature field at 10 minutes



(b) Temperature field at 38 minutes



(c) Temperature field at 50 minutes



(d) Temperature field at 60 minutes

Figure 81: Temperature fields in the plan of the steel portal frame the nearest of the fire source

A.4. Scenario S.1.3

This scenario concerns a 1400m² supermarket with a shelf storage system. The source of fire is located in the middle of central double-row shelves.

The calculated HRR is shown in Figure 82. The plan views in Figure 83 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same. As for the two other scenarios involving shelves, the storage configuration does not allow to obtain a flashover. Indeed, the low quantity of fuel coupled with the important roof height leads to an important dilution. Moreover, the roof opening area is enough to allow an efficient evacuation of smokes and hot gases outside the building. The propagation occurs gradually and is driven by radiative heat fluxes. At 32 minutes, the five shelves that can be involved in fire are partially burning (Figure 83d). The spreading rate is fast enough to propagate the fire to the entire quantity of fuel stored on shelves before the extinction of the combustible involved in the ignition. A peak HRR is obtained at 51 minutes. The amount of fuels gradually decreases with the combustion until the total extinction of the fire at 120 minutes.

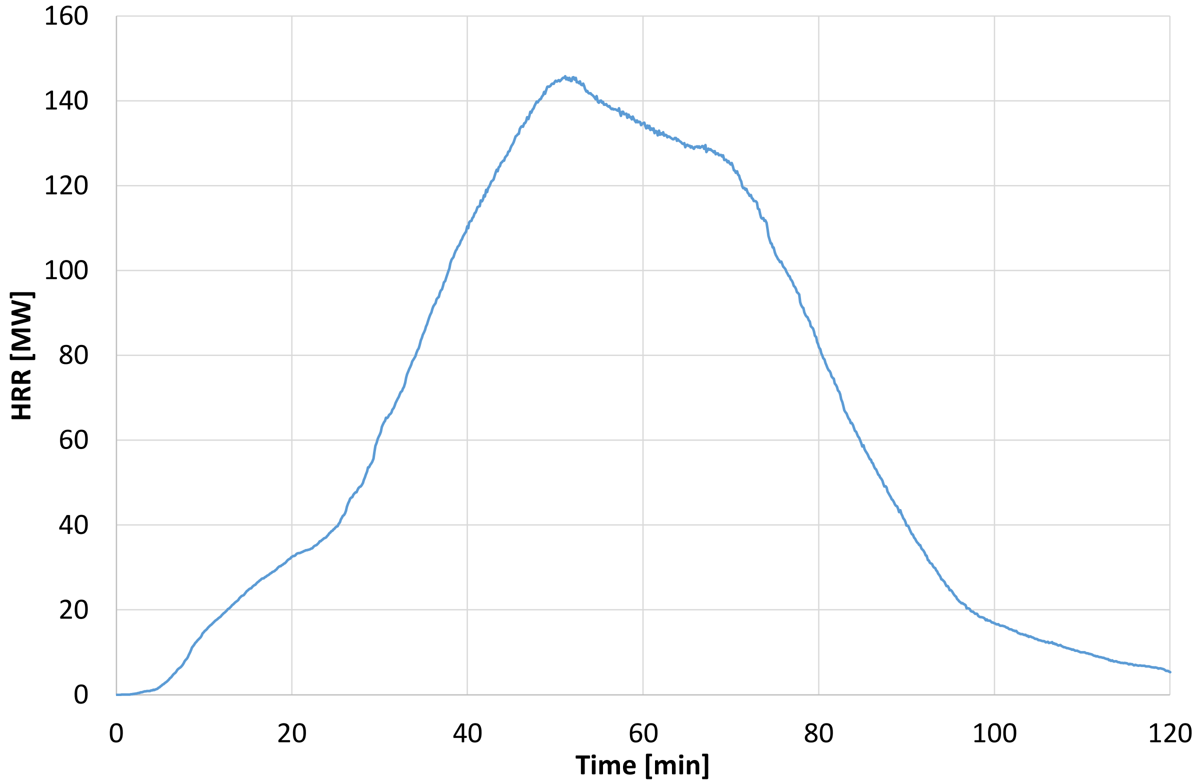


Figure 82: HRR calculated for the scenario S.1.3

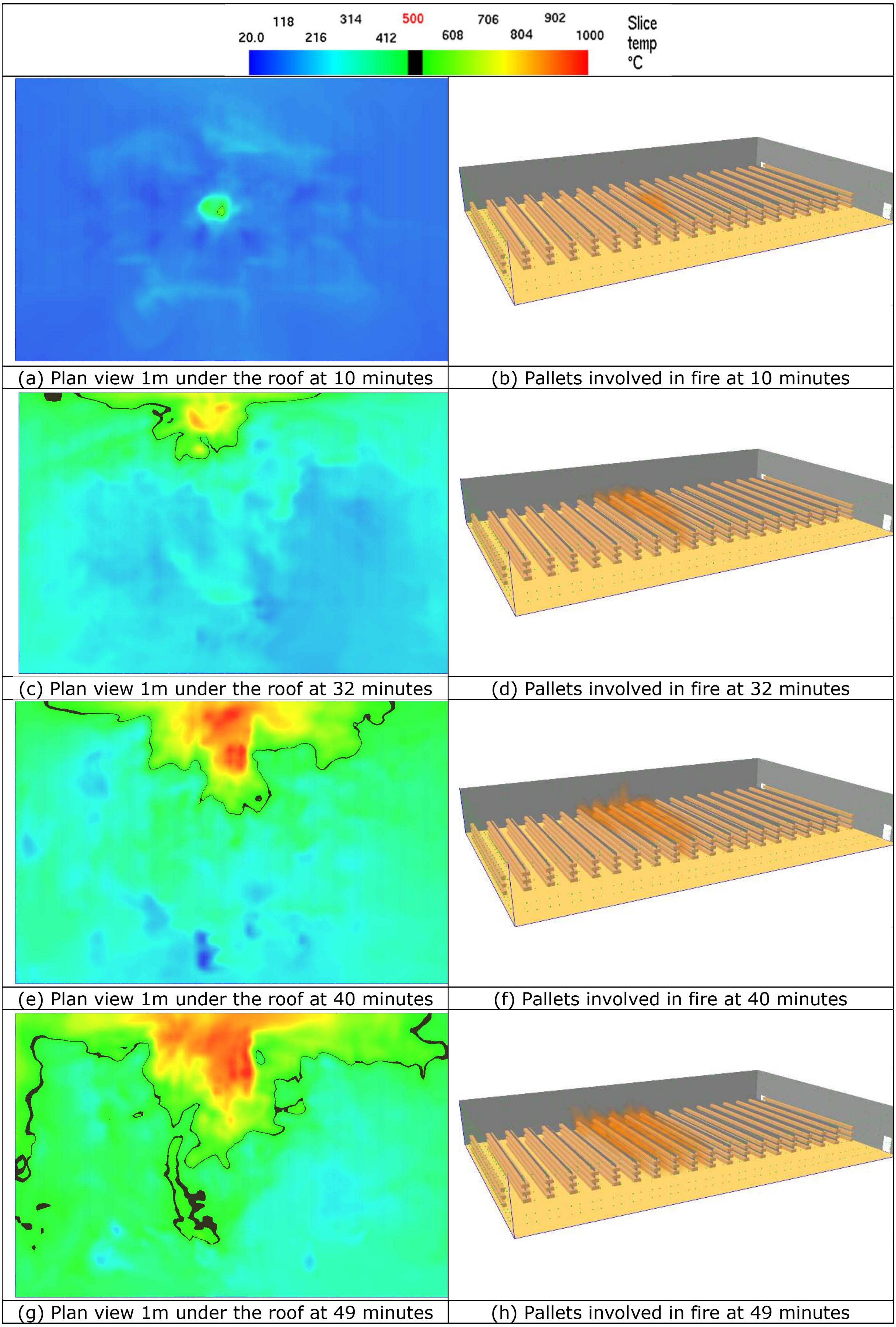


Figure 83: Temperature fields under the roof and surfaces involved in the fire

Figure 84 shows the gas temperatures calculated at 1m under the roof directly above location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present) close or far away from the fire source (as indicated in Figure 85). During the first 27 minutes, all the temperatures under the roof are lower than 400°C. Only the thermocouples T1, T2 and T3 (near the involved shelves) reach a temperature over 600°C after 29 to 44 minutes. At 48 minutes, all the temperatures reach their maximum value or a plateau of 880, 810, 660, 510 and 440°C at the thermocouples T1 to T5, respectively. After 75 minutes, gas temperatures start to decay as the fuel load is consumed.

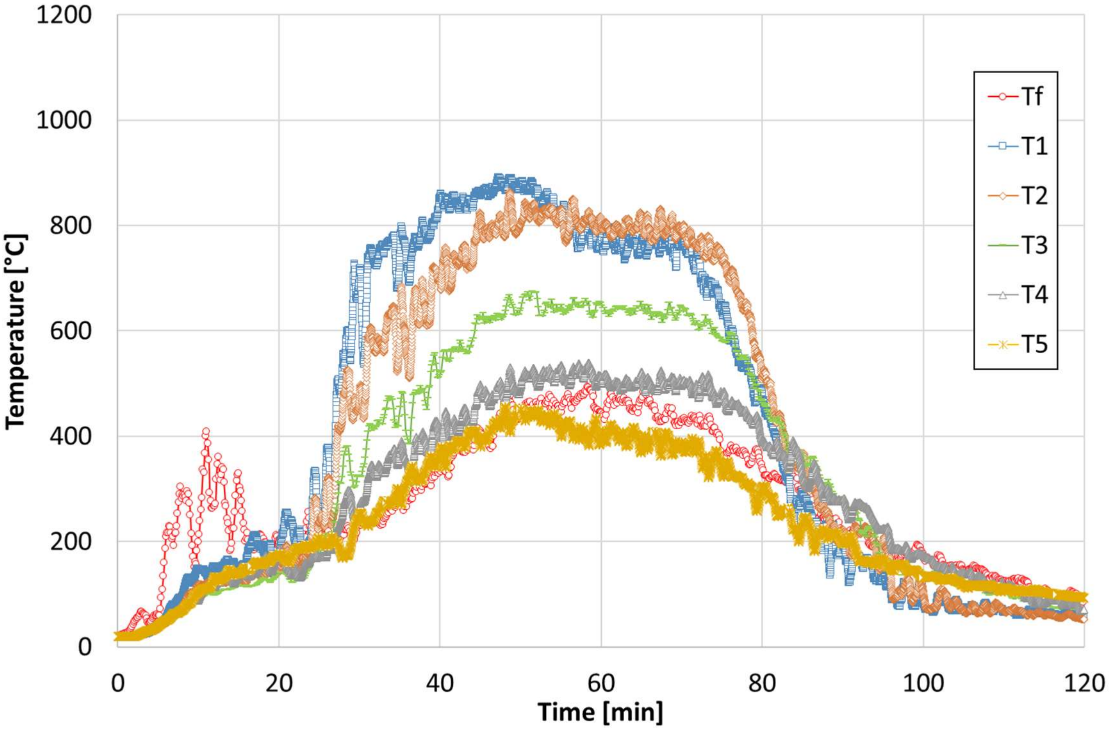


Figure 84: Gas temperature at different locations under the roof

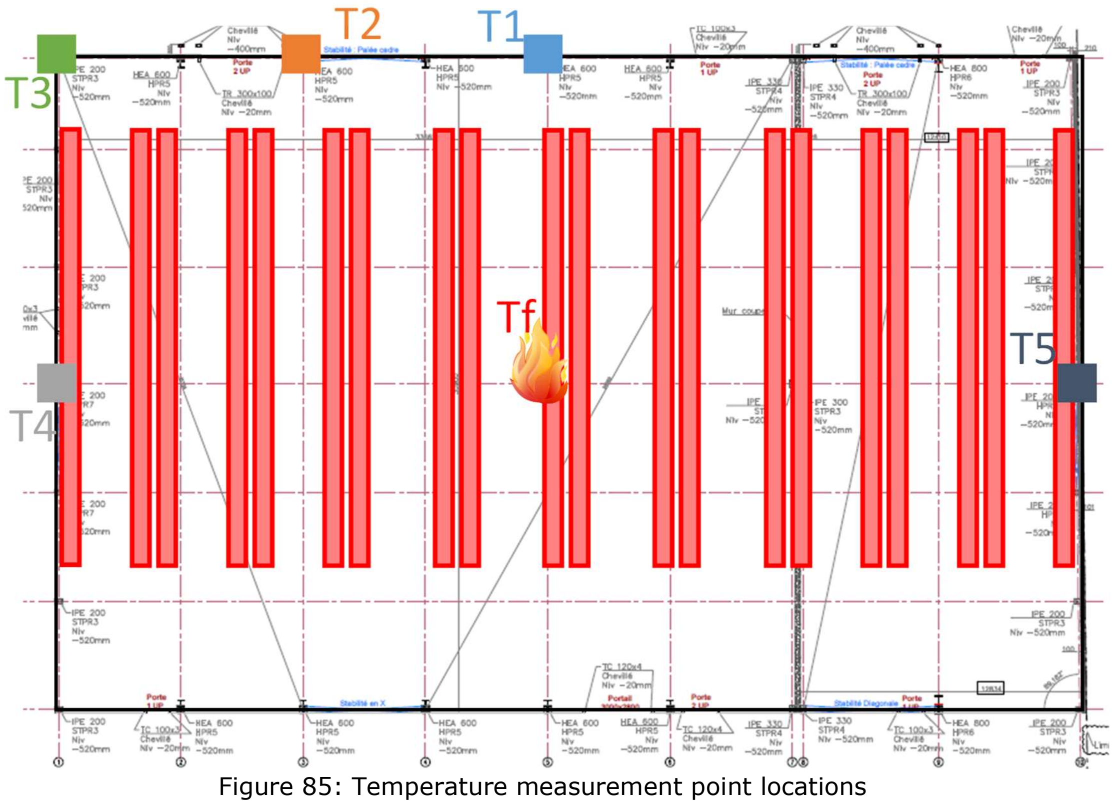


Figure 85: Temperature measurement point locations

Gas temperatures calculated in the plan of the steel portal frame the nearest of the fire source are shown Figure 86. It can be observed that hot gases are only present near the wall with the thermocouple T1. This phenomenon may be due to the presence of doors on the opposite wall. The incoming fresh air dilutes hot gases near this zone and may not allow the increase of temperature.

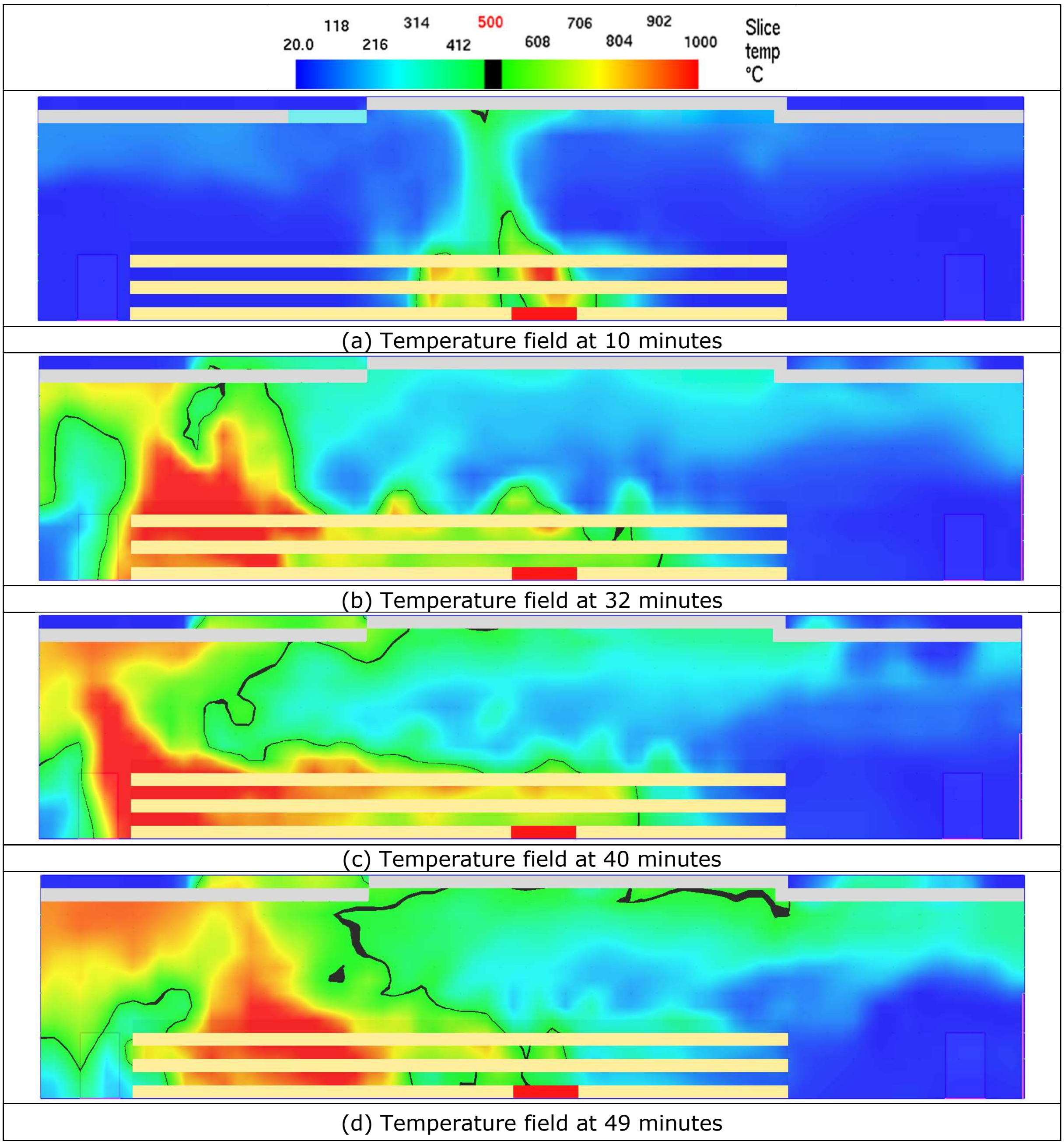


Figure 86: Temperature fields in the plan of the steel portal frame the nearest of the fire source

A.5. Scenario I.1.1

This scenario concerns a 1400m² industrial building with a bulk storage, located near one of the larger building walls.

The calculated HRR is shown in Figure 87. It should be noticed that it is prescribed in this scenario. The intensity of the fire increases until reaching a plateau of 32 MW at 28 minutes. The plan views in Figure 88 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. In this scenario, the quantity of heat produced is not important enough to obtain a large zone of hot gases under the roof. Only the zone near the combustible reaches temperatures over 500°C. After 45 minutes, the fire decays due to a lack of combustible.

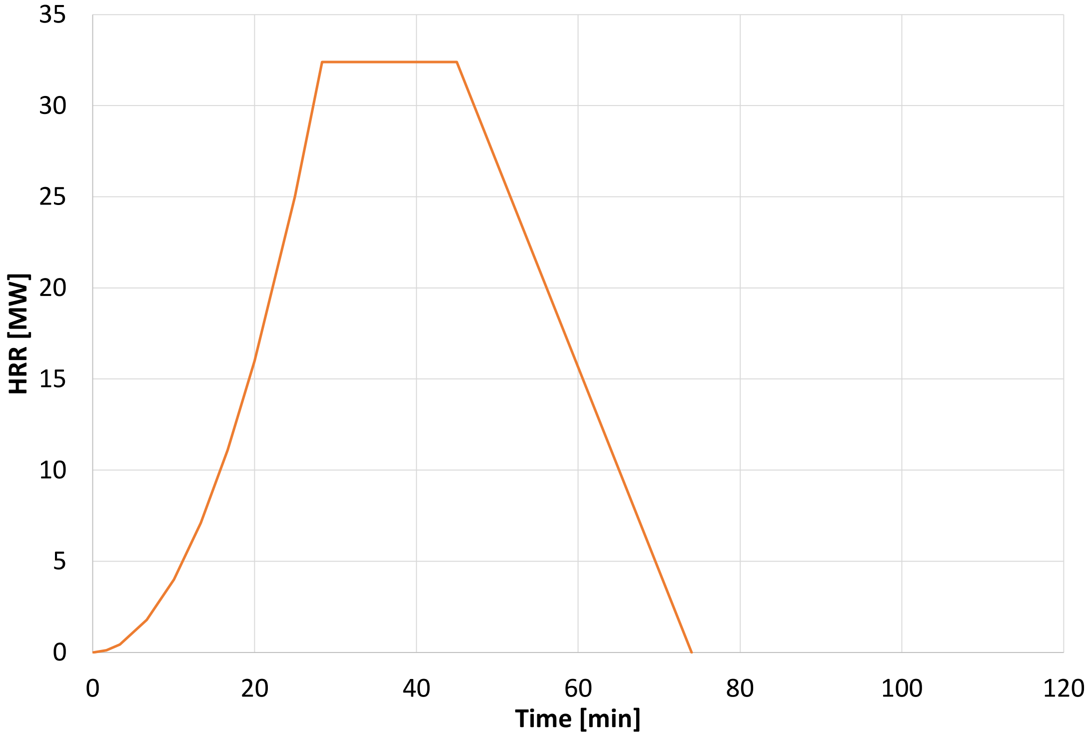
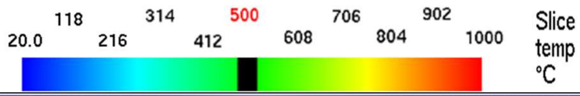
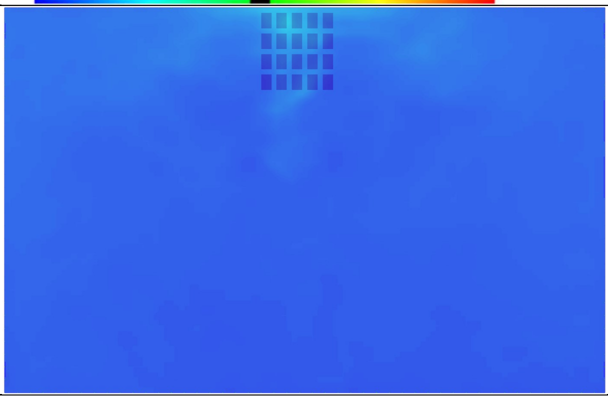
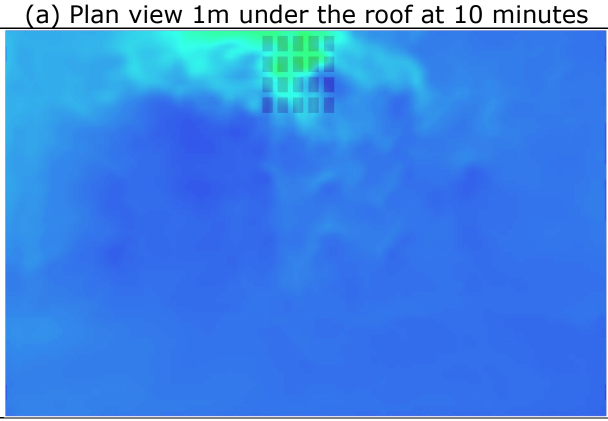


Figure 87: HRR calculated for the scenario I.1.1

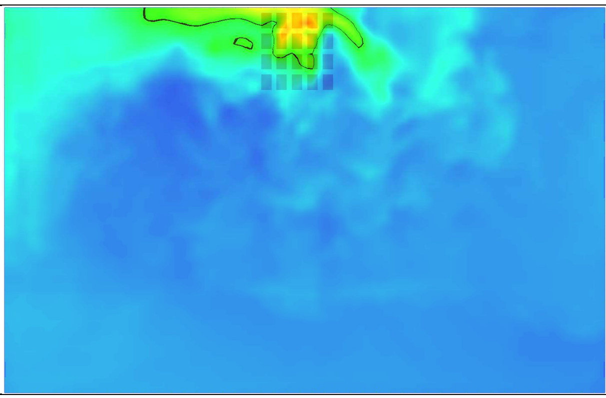




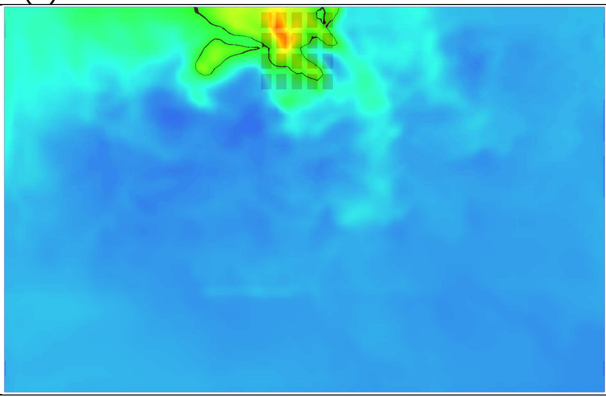
(a) Plan view 1m under the roof at 10 minutes



(c) Plan view 1m under the roof at 20 minutes



(e) Plan view 1m under the roof at 29 minutes



(g) Plan view 1m under the roof at 31 minutes

Figure 88: Temperature fields under the roof

Figure 89 shows the gas temperatures calculated at 1m under the roof directly above the ignition position and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 90). The temperatures of all the thermocouples increase with the HRR. It should be noticed that the presence of the wall deflects the trajectory of the flame. Thus, highest temperatures are obtained at thermocouple T1, with 600°C and 720°C at 26 and 29 minutes, respectively. Only thermocouple T2 shows temperature over 400°C, with 500°C at 33 minutes.

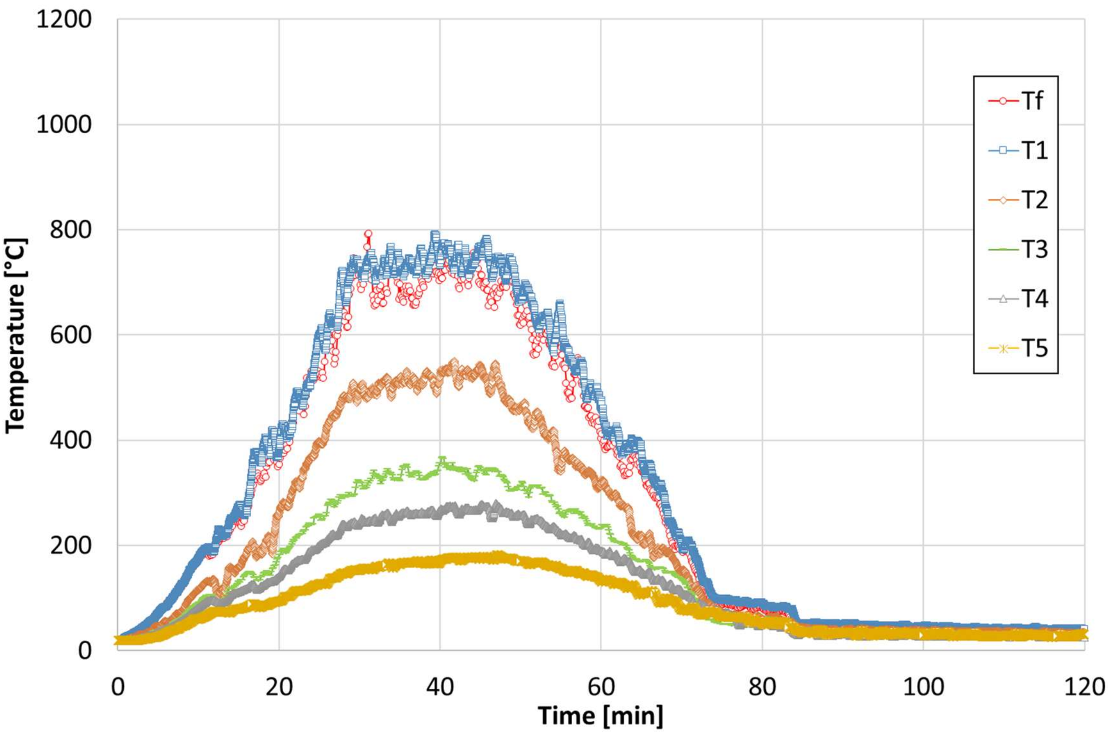


Figure 89: Gas temperature at different locations under the roof

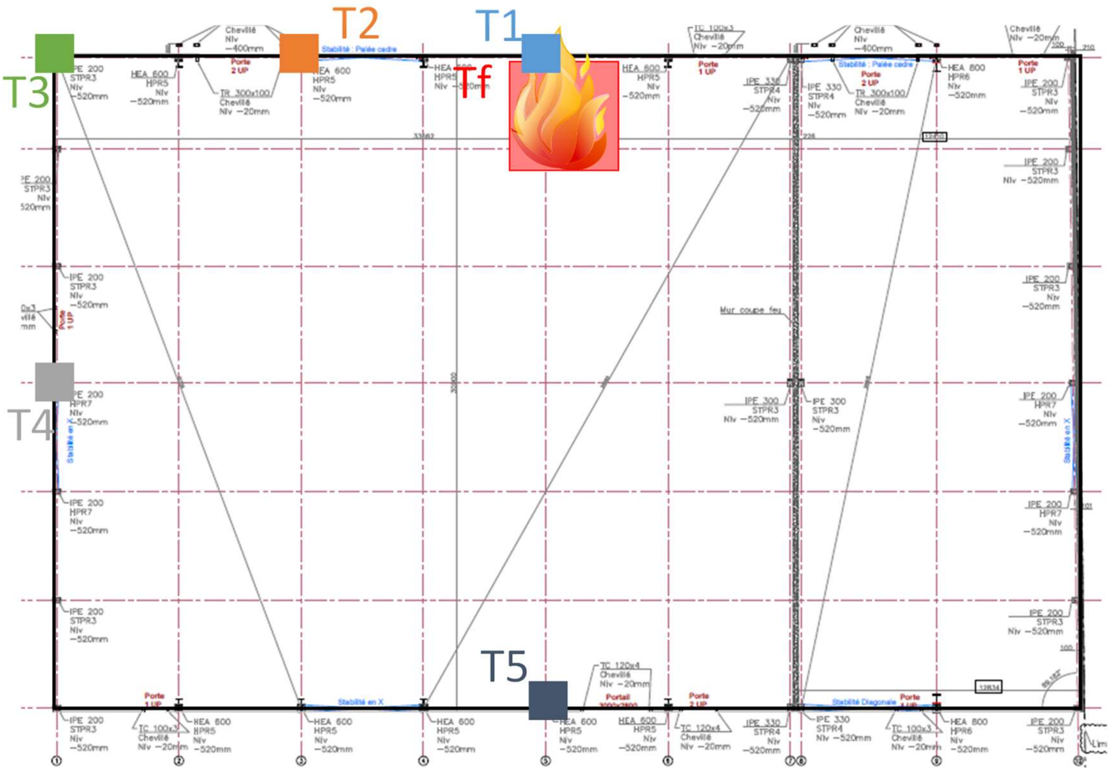


Figure 90: Temperature measurement point locations

Gas temperatures calculated at different heights wall nearest the fire source, at the same location as thermocouple T1, are shown in Figure 91. It can be noted that gas temperatures increase uniformely along the height during the first 10 minutes of fire. Then, small differences can be observed until the plateau at 39 minutes. Temperatures over 600°C are obtained above 4m, with a highest temperature of 800°C at 6 m height. The high temperature fluctuations at 2 and 3 m height suggest the presence of a turbulent flame near the thermocouples.

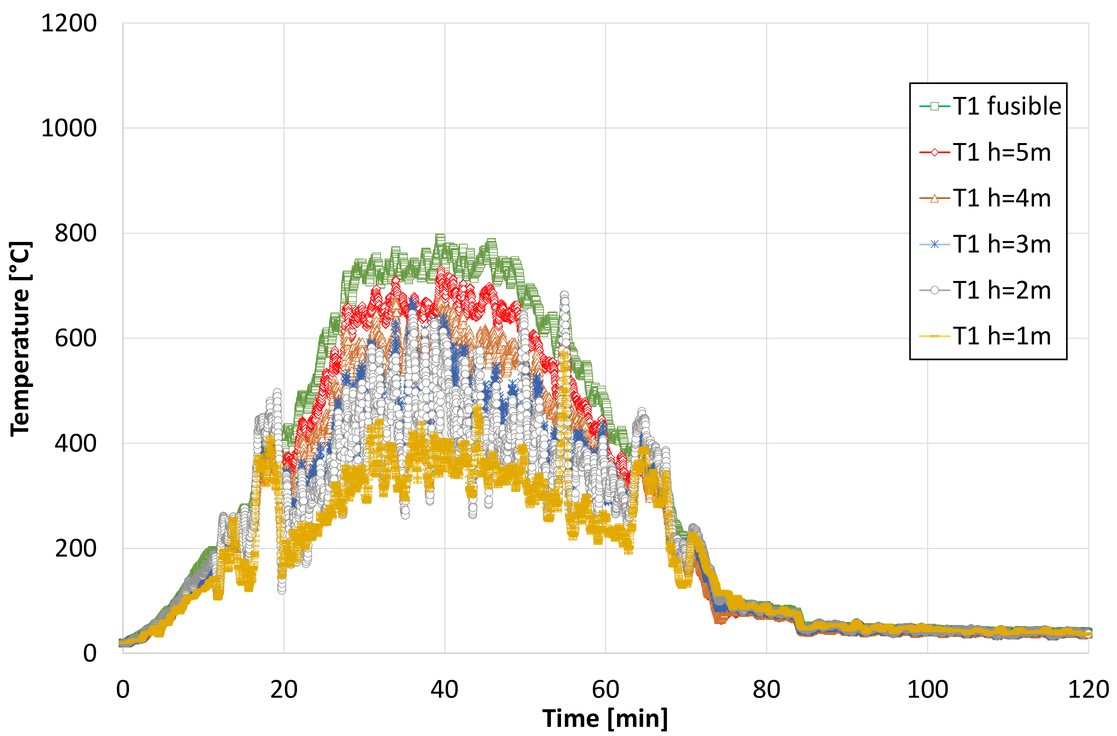
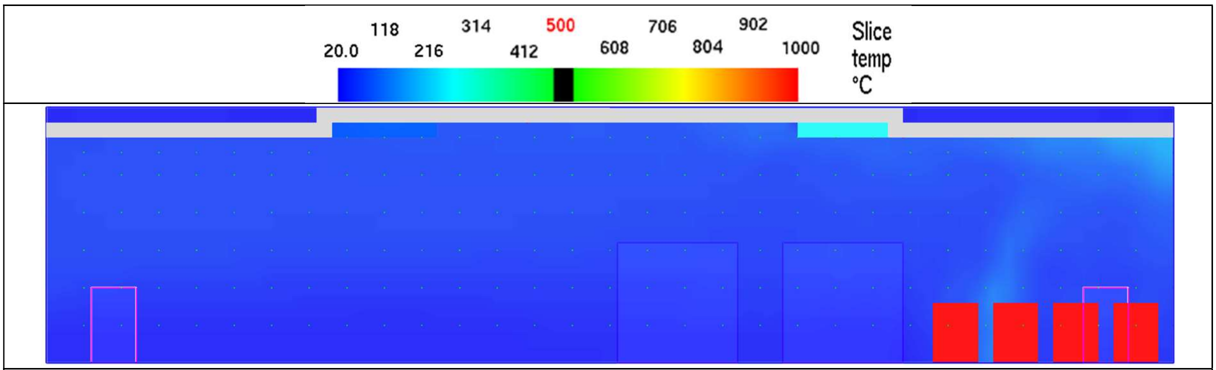
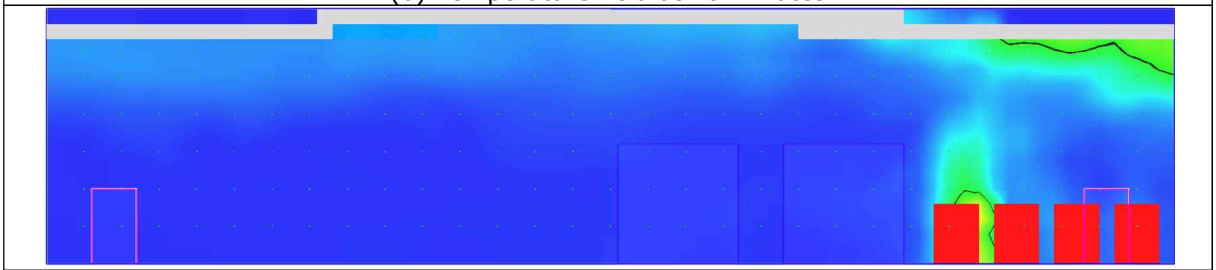


Figure 91: Gas temperatures versus time along the wall height at the location of thermocouple T1

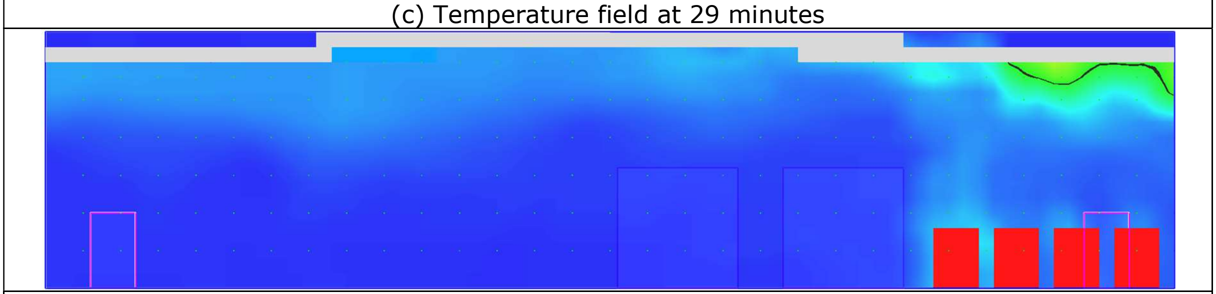


(a) Temperature field at 10 minutes

(b) Temperature field at 20 minutes



(c) Temperature field at 29 minutes



(d) Temperature field at 31 minutes

Figure 92: Temperature fields in the plan of the steel portal frame the nearest of the fire source

A.6. Scenario I.1.3

This scenario concerns a 1400m² industrial building with a bulk storage, located in the middle of the building.

The calculated HRR is shown in Figure 87. It should be noticed that it is prescribed in this scenario. The intensity of the fire increases until reaching a plateau of 32 MW at 28 minutes. The plan views in Figure 94 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. In this scenario, the quantity of heat produced is not important enough to obtain a zone of hot gases under the roof. Only a small zone above the fire source reaches temperatures over 500°C. After 45 minutes, the fire decays due to a lack of combustible.

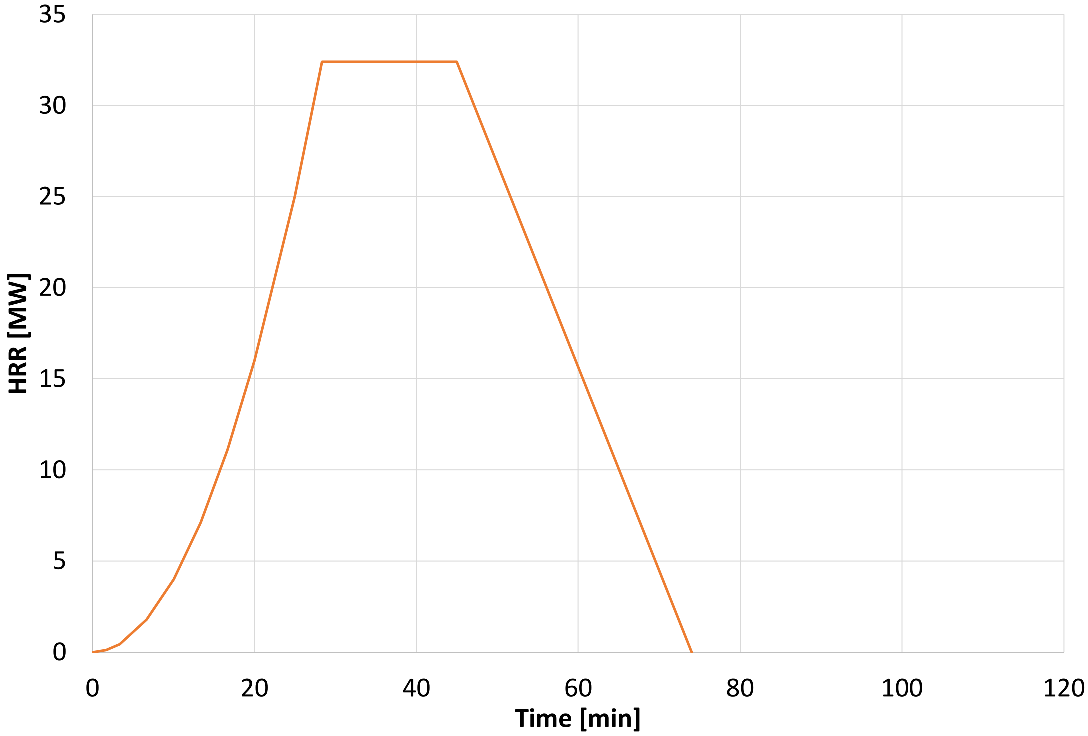
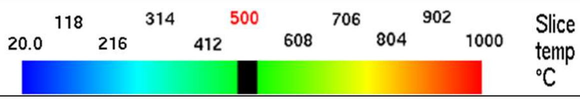
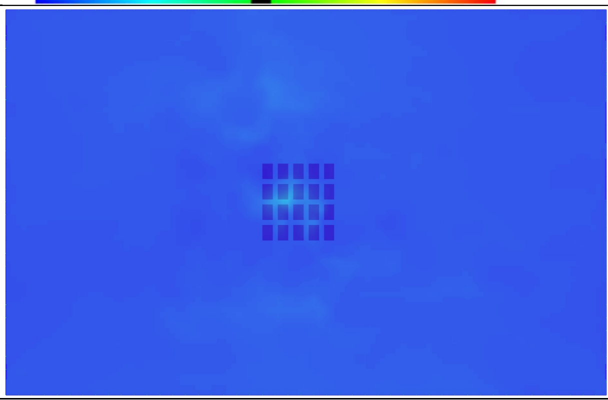
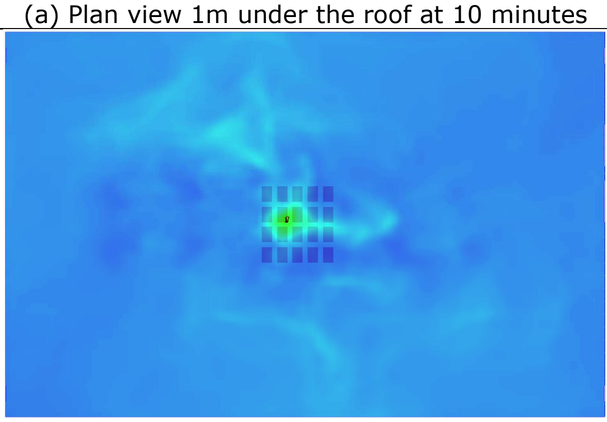


Figure 93: HRR calculated for the scenario I.1.3

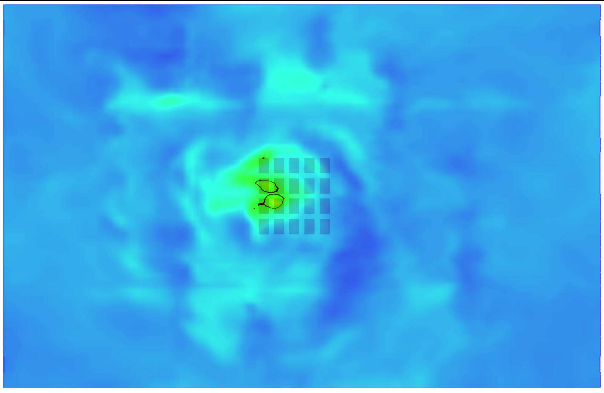




(a) Plan view 1m under the roof at 10 minutes



(c) Plan view 1m under the roof at 20 minutes



(e) Plan view 1m under the roof at 29 minutes

Figure 94: Temperature fields under the roof

Figure 95 shows the gas temperatures calculated at 1m under the roof directly above the ignition position and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 96). The temperatures of all the thermocouples Tf and T1 to T5 increase with the HRR. Temperatures increase uniformely for all the walls during the 20 first minutes of fire. Then, only the thermocouple T1 shows gas temperatures slightly over 200°C during the plateau phase. It should be noticed that even the temperature above the fire source hardly exceeds 600°C at 40 minutes.

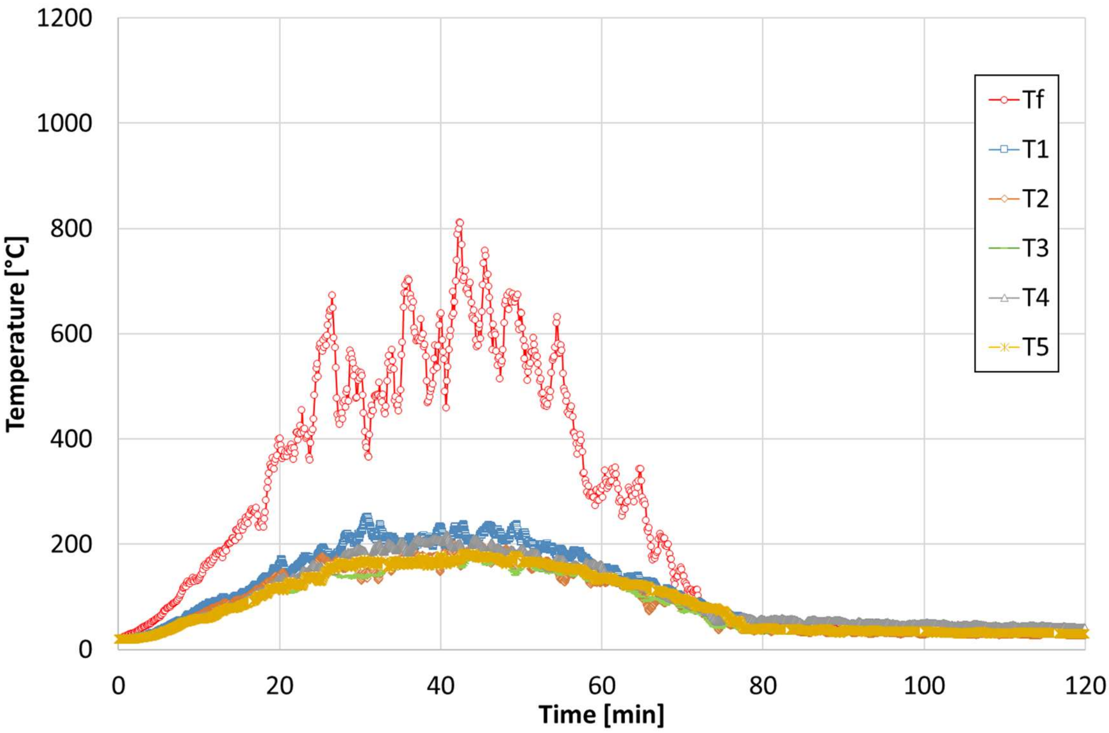


Figure 95: Gas temperature at different locations under the roof

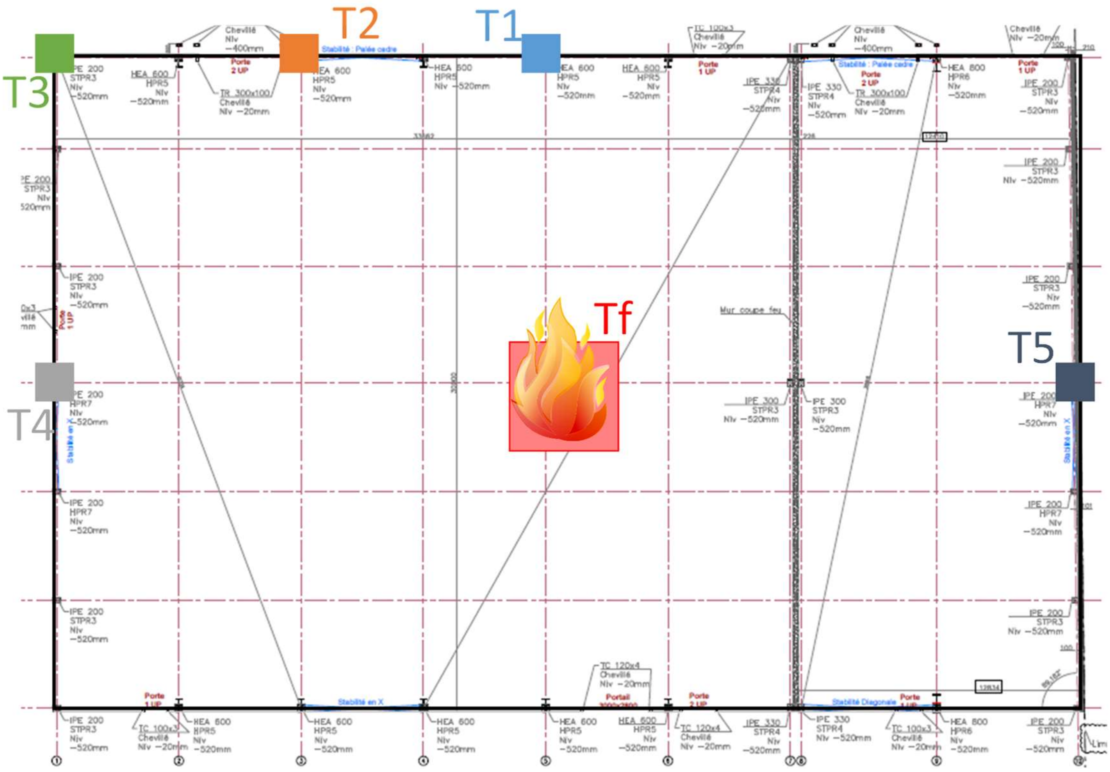
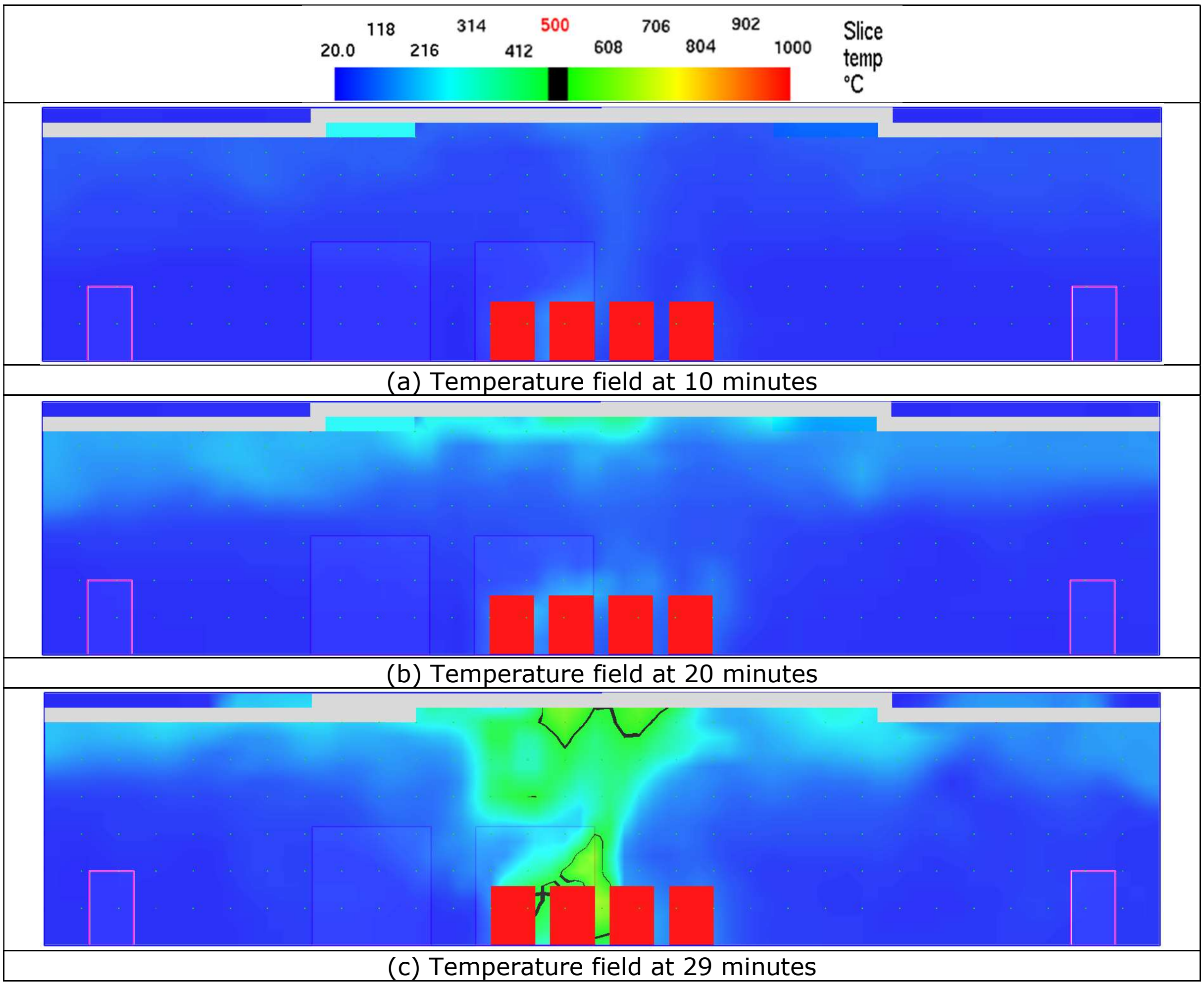


Figure 96: Temperature measurement point locations



(a) Temperature field at 10 minutes

(b) Temperature field at 20 minutes

(c) Temperature field at 29 minutes

Figure 97: Temperature fields in the plan of the steel portal frame the nearest of the fire source

A.7. Scenario W.2.1

This scenario concerns a 3100m² warehouse with a racking storage system. The fire starts at the end of a central double row rack, near one of the longer building walls.

The calculated HRR is shown in Figure 98. The plan views in Figure 99 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. It can be noted that a flashover occurs between 25 and 30 minutes due to the quick fire propagation at the upper part of the rack storage. Although the opening area is important (9% of the roof surface), the natural smoke extraction flow is not enough to efficiently evacuate the heat generated by the fire. After 70 minutes, the fire starts to decrease until the total extinction of the fire at 77 minutes due to a lack of combustible.

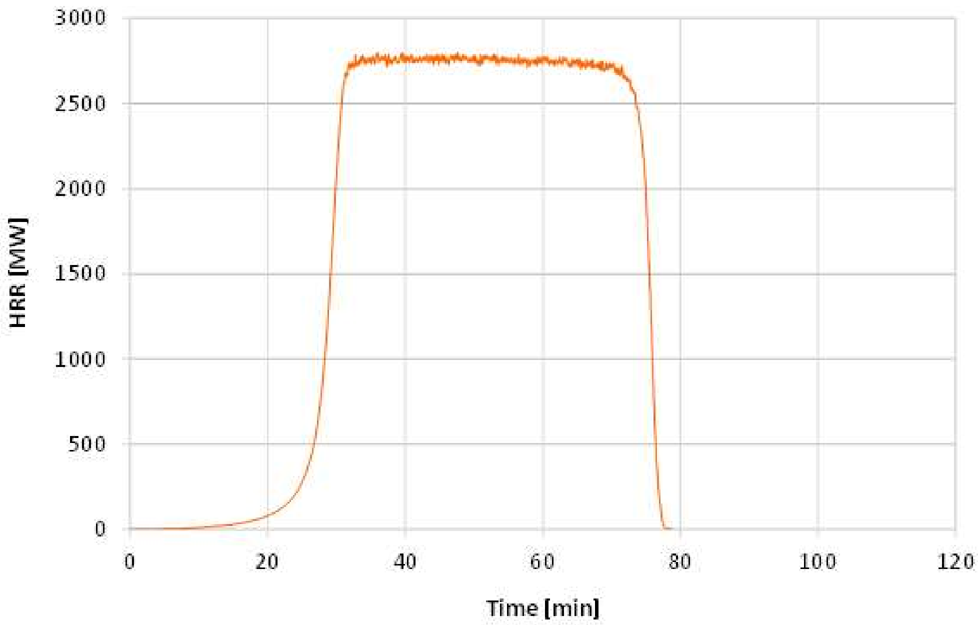
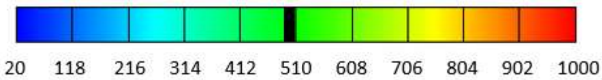
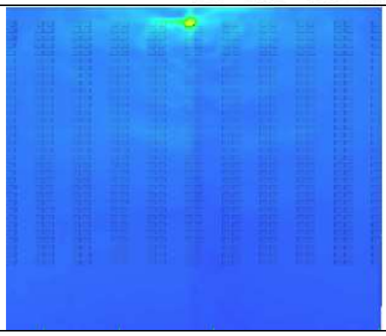
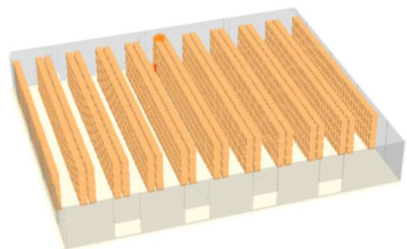
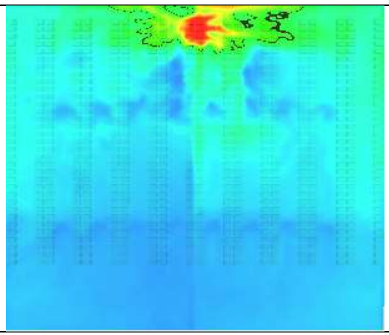
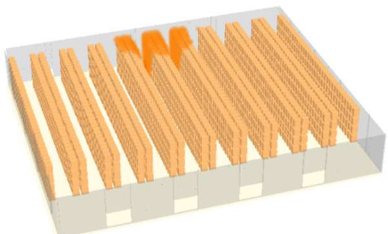


Figure 98: HRR calculated for the scenario W.2.1

	
	
(a) Plan view 1m under the roof at 10 minutes	(b) Pallets involved in fire at 10 minutes
	
(c) Plan view 1m under the roof at 20 minutes	(d) Pallets involved in fire at 20 minutes

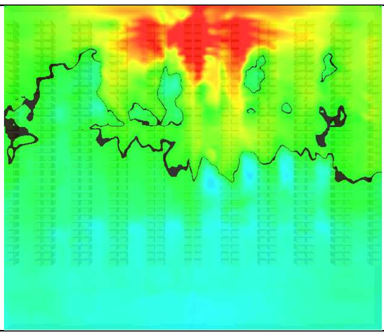
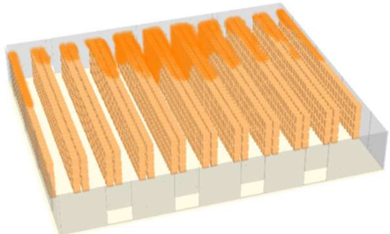
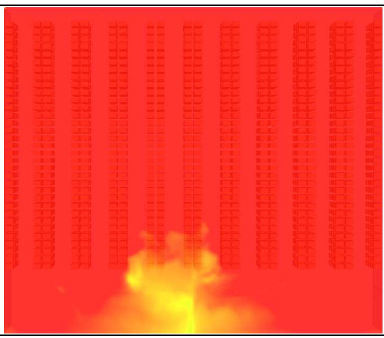
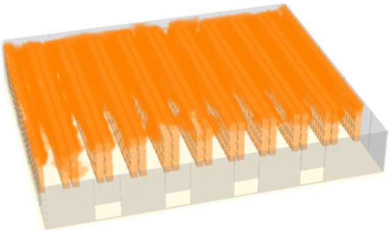
	
(e) Plan view 1m under the roof at 25 minutes	(f) Pallets involved in fire at 25 minutes
	
(g) Plan view 1m under the roof at 30 minutes	(h) Pallets involved in fire at 30 minutes

Figure 99: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 100 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 101). Gas temperatures reach the highest value of 1000°C at 13 minutes above the fire source (thermocouple Tf) and at 24 minutes at thermocouple T1. At 30 minutes, the highest temperature of 1000°C is obtained for almost the whole surface of the building at 9 m height (Figure 99g). Then, gas temperatures decrease during the decay phase of the fire.

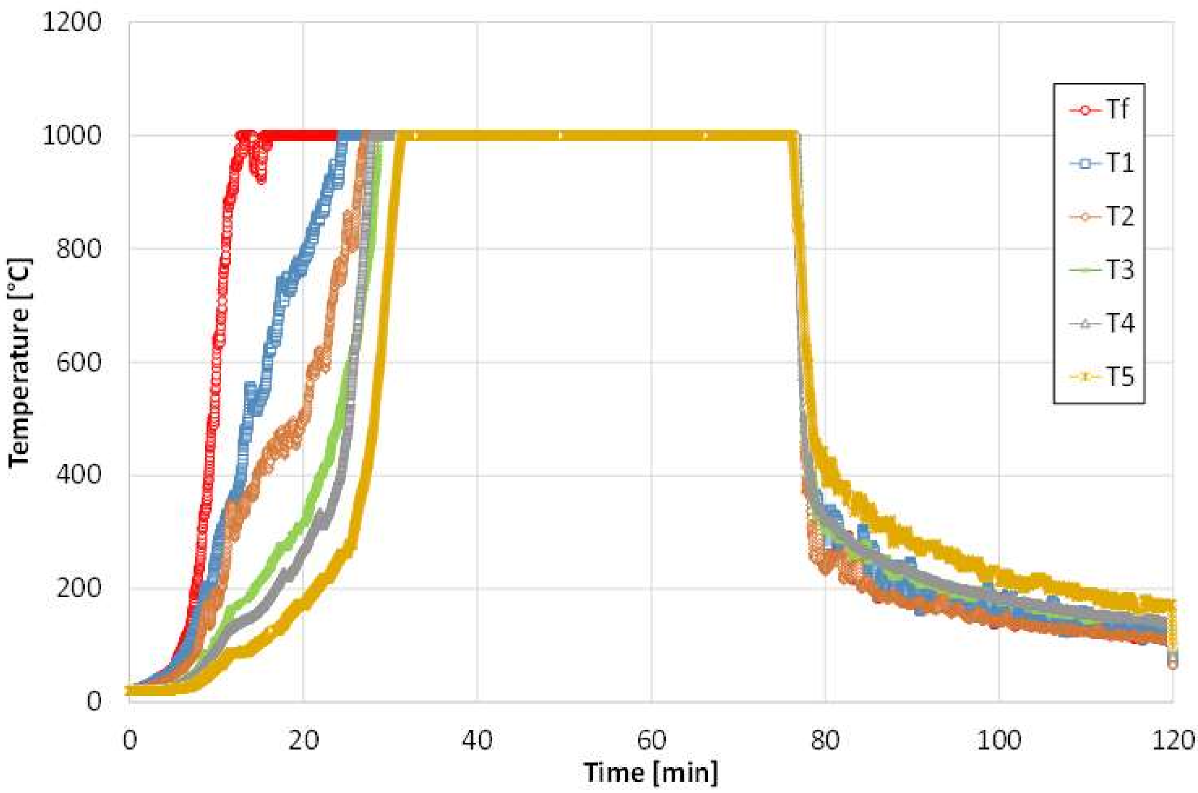


Figure 100: Gas temperature at different locations under the roof

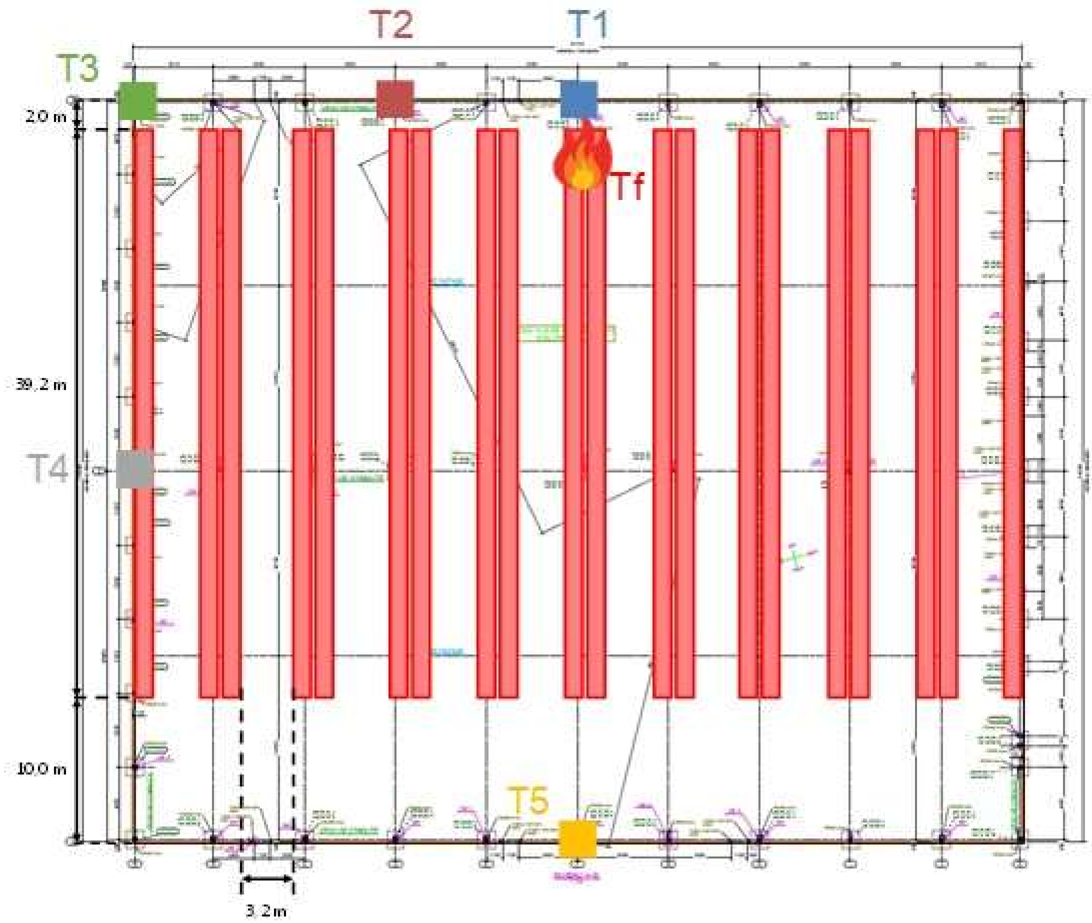


Figure 101: Temperature measurement point locations

Gas temperatures calculated at different wall heights nearest the fire source, at the same location as thermocouple T1 are shown in Figure 102. The gas temperature increases more slowly at the lower parts. However, high gas temperatures are observed in almost all the volume of the building after 30 minutes.

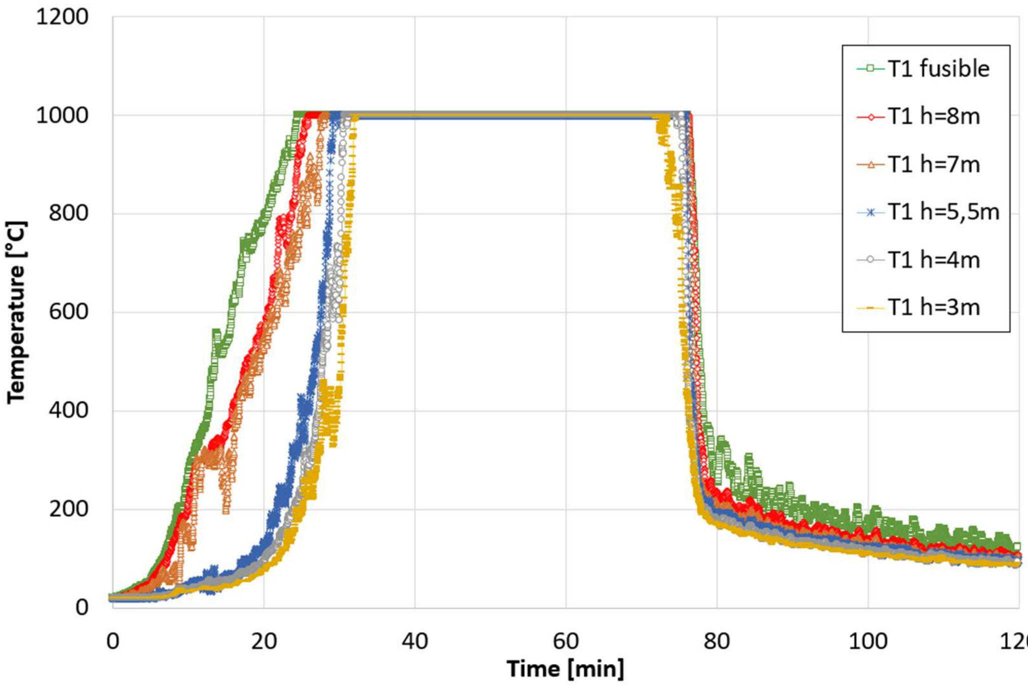
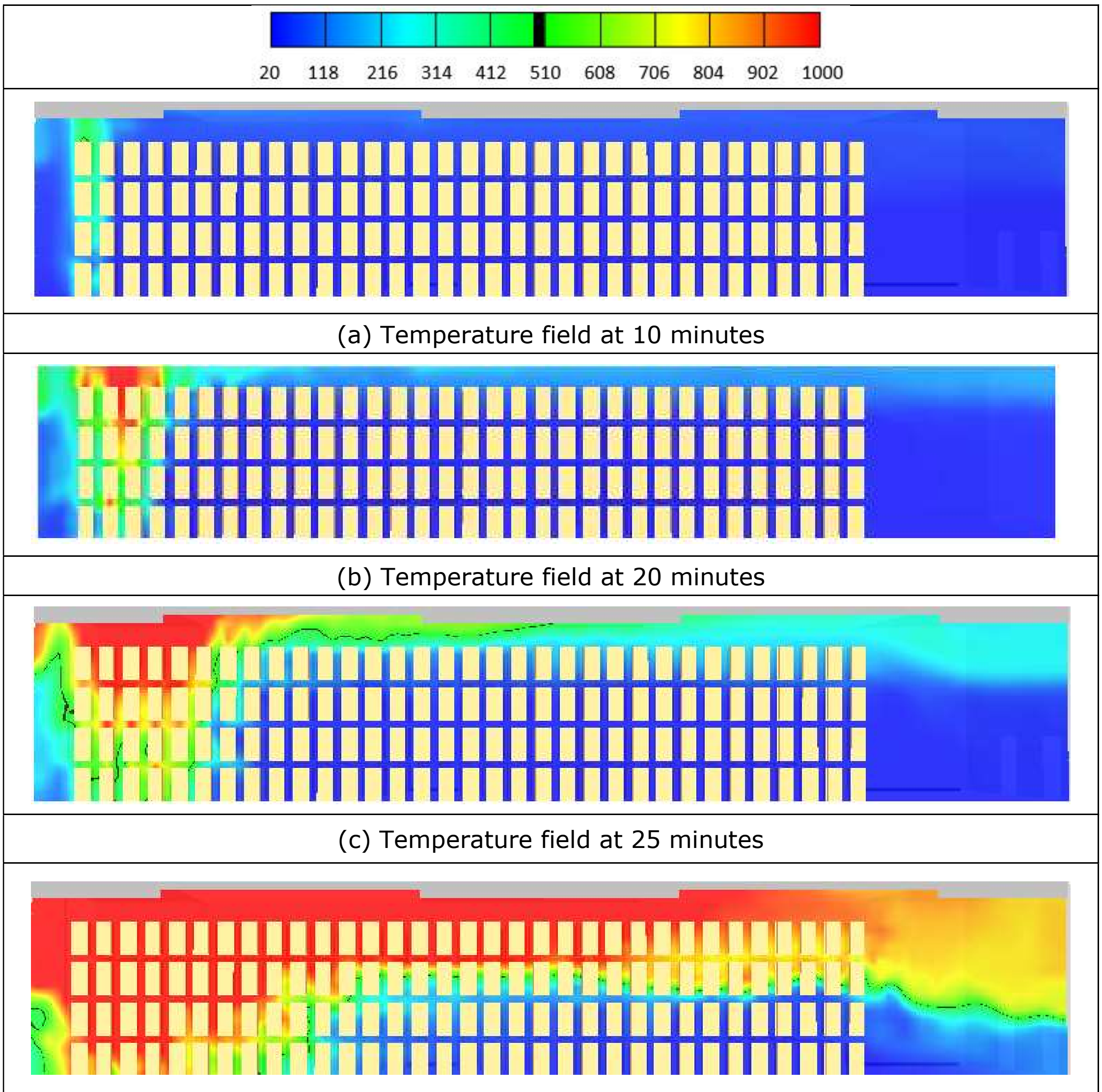


Figure 102: Gas temperatures versus time along the wall height at the location of thermocouple T1



(a) Temperature field at 10 minutes

(b) Temperature field at 20 minutes

(c) Temperature field at 25 minutes

(d) Temperature field at 30 minutes

Figure 103: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.8. Scenario W.2.2

This scenario concerns a 3100m² warehouse with a racking storage system. The fire starts in the middle of a single row rack, near one of the shorter building walls.

The calculated HRR is shown in Figure 104. The plan views in Figure 105 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. It can be noted that a flashover occurs between 23 and 27 minutes due to the quick fire propagation at the upper part of the rack storage. Although the opening area is important (9% of the roof surface), the natural smoke extraction flow is not enough to effectively evacuate the heat generated by the fire. After 70 minutes, the fire starts to decrease until the total extinction of the fire at 77 minutes due to a lack of combustible.

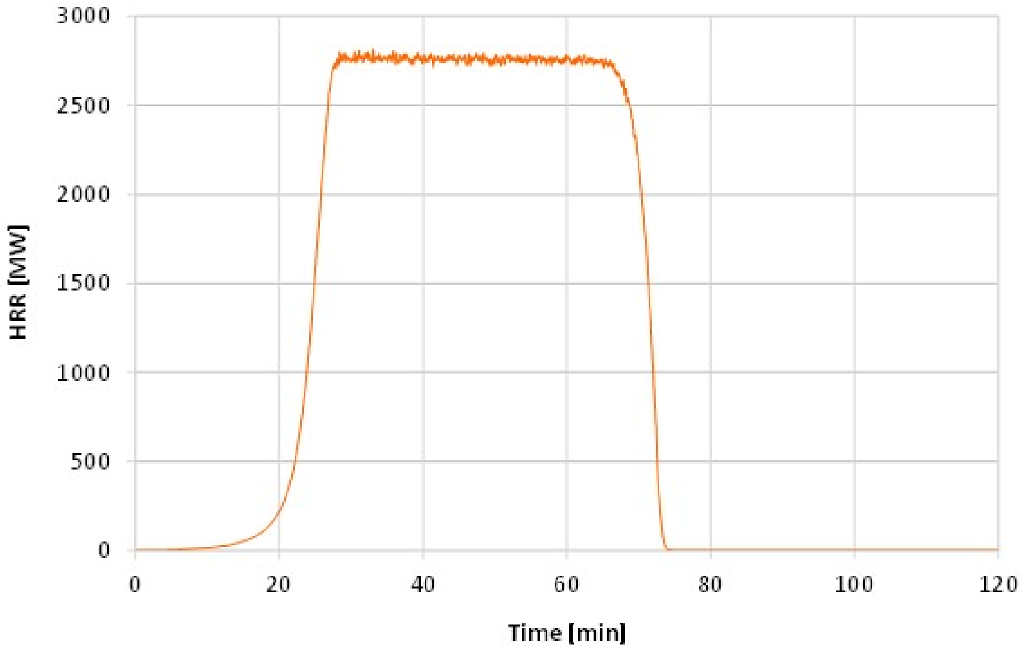
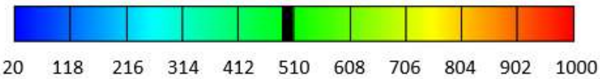
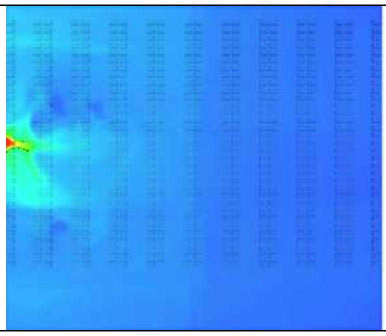
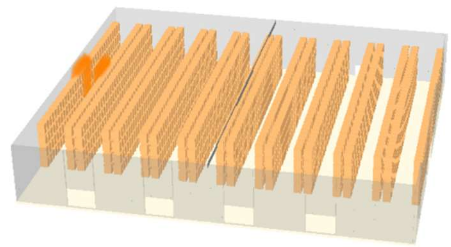
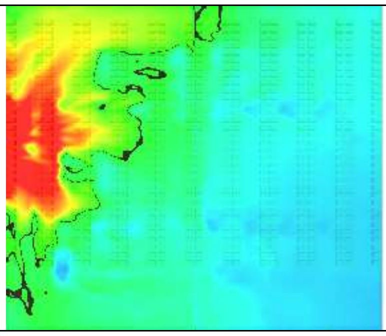
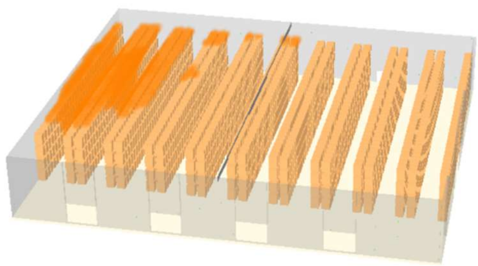
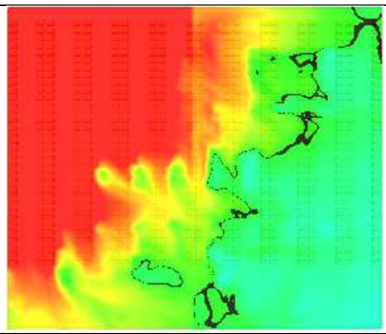
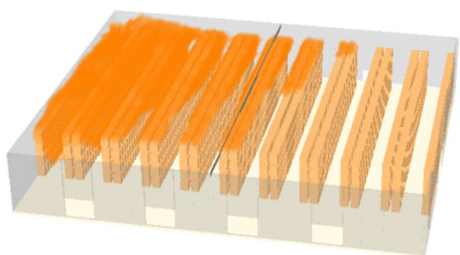


Figure 104: HRR calculated for the scenario W.2.2



	
(a) Plan view 1m under the roof at 10 minutes	(b) Pallets involved in fire at 10 minutes
	
(c) Plan view 1m under the roof at 20 minutes	(d) Pallets involved in fire at 20 minutes
	
(e) Plan view 1m under the roof at 23 minutes	(f) Pallets involved in fire at 23 minutes

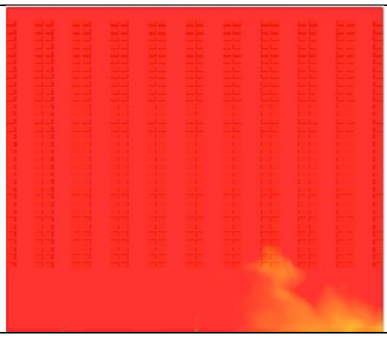
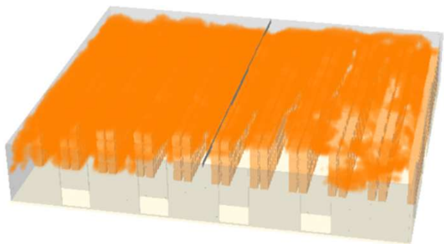
	
(g) Plan view 1m under the roof at 27 minutes	(h) Pallets involved in fire at 27 minutes

Figure 105: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 106 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), close or far away from the fire source (as indicated in Figure 107). Gas temperatures reach 1000°C at 8 minutes above the ignition position (thermocouple Tf) and at the thermocouple T1. At 27 minutes, the highest temperature of 1000°C is obtained for almost the whole surface of the building at 9 m height (Figure 99g).

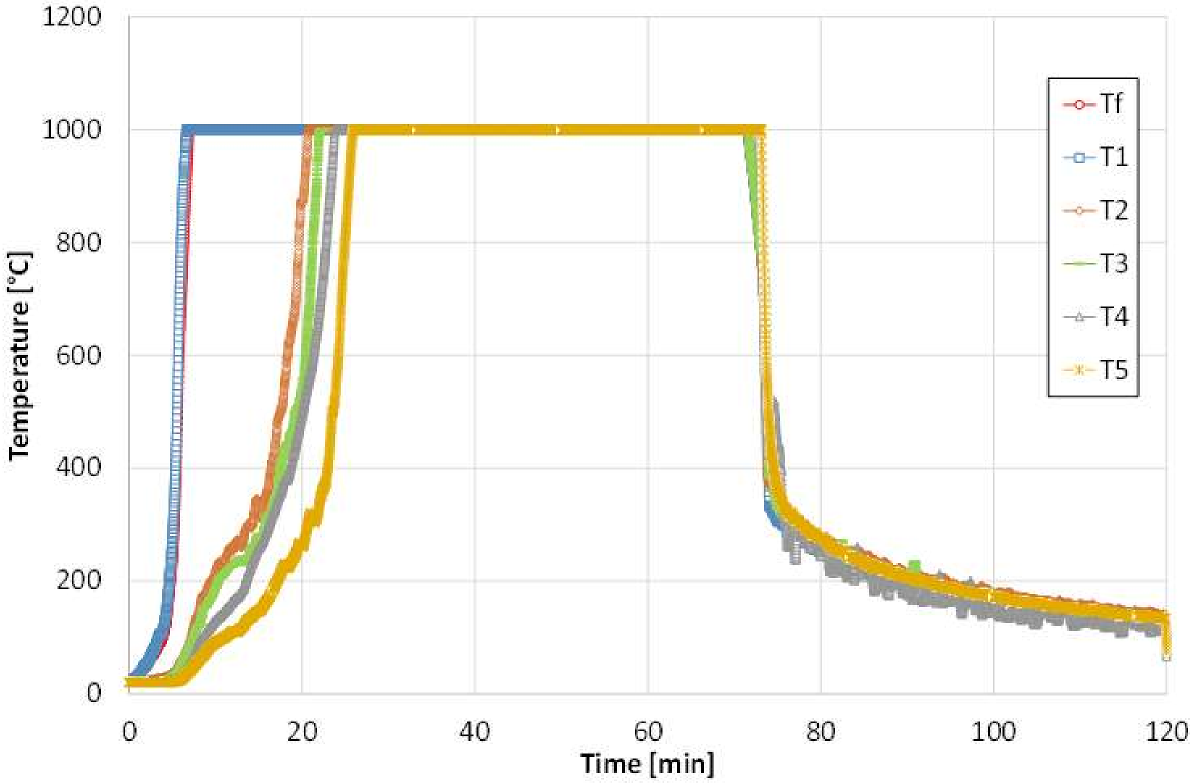


Figure 106: Gas temperature at different locations under the roof

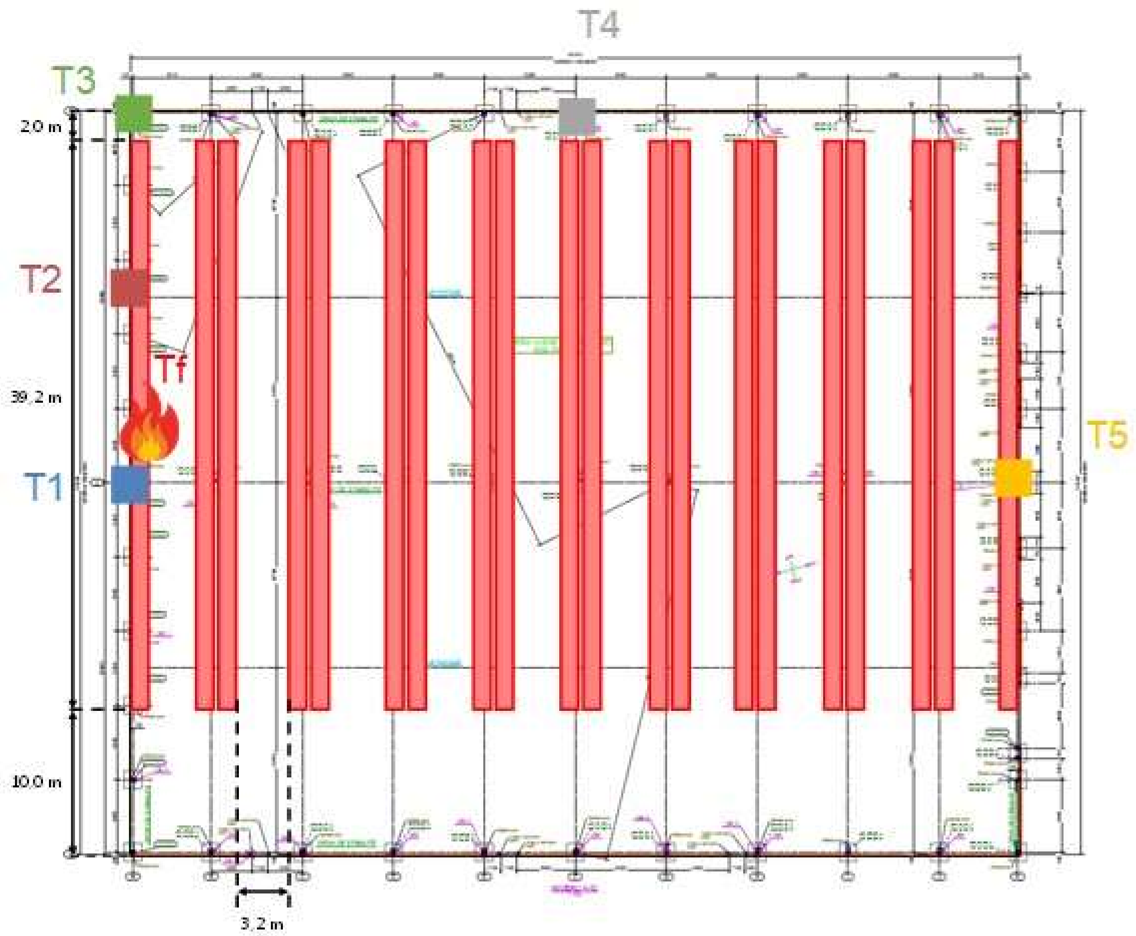


Figure 107: Temperature measurement point locations

Gas temperatures calculated at different wall heights nearest the fire source, at the same location as thermocouple T1, are shown in Figure 108. It can be noted the hot gases are uniformely distributed along the height.

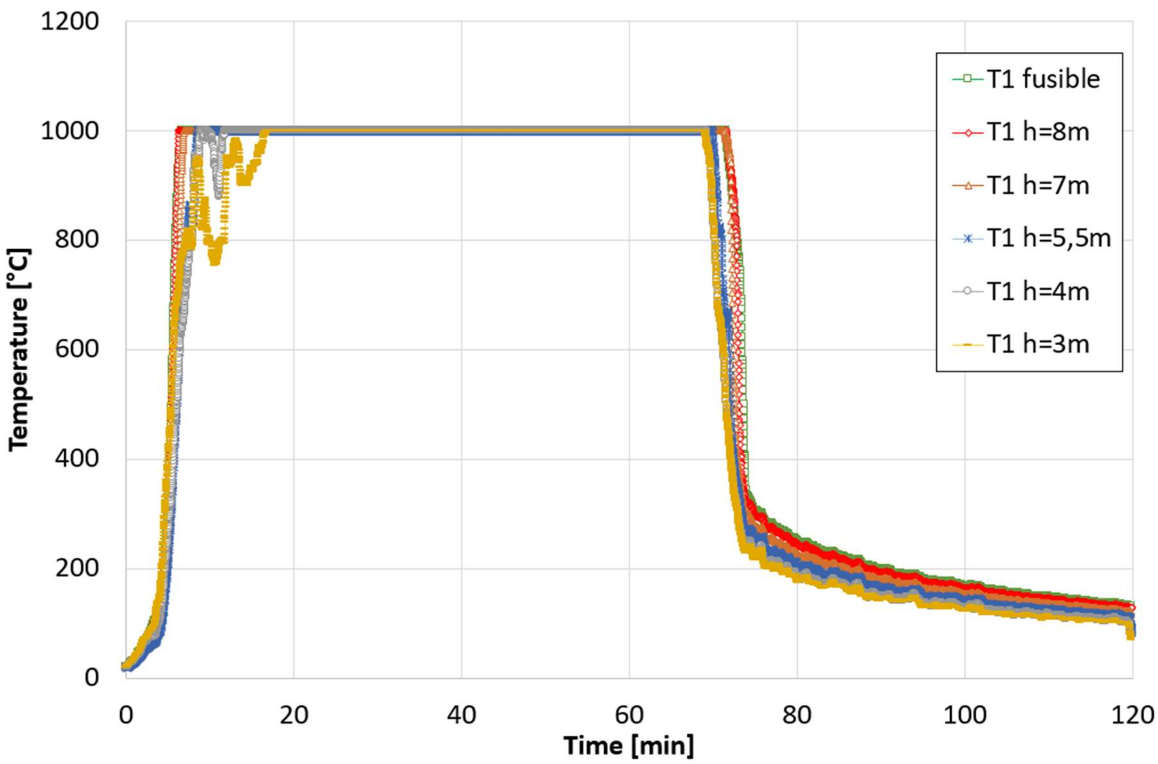
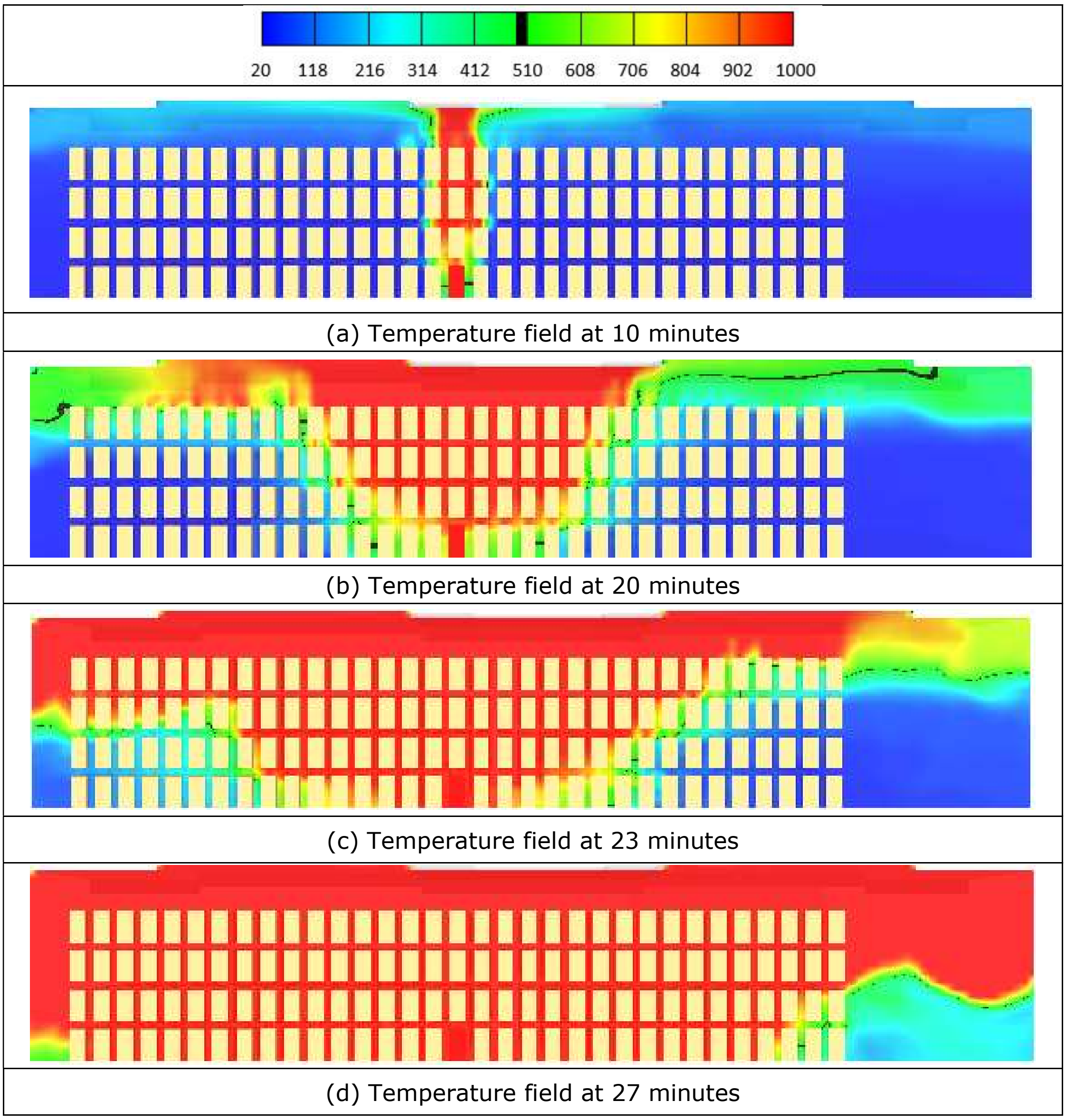


Figure 108: Gas temperatures versus time along the wall height at the location of thermocouple T1



(a) Temperature field at 10 minutes

(b) Temperature field at 20 minutes

(c) Temperature field at 23 minutes

(d) Temperature field at 27 minutes

Figure 109: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.9. Scenario W.2.3

This scenario concerns a 3100m² warehouse with a racking storage system. The source of fire is situated in the middle of a central double row rack.

The calculated HRR is shown in Figure 110. The plan views in Figure 111 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. It can be noted that a flashover occurs between 20 and 25 minutes due to the quick fire propagation at the upper part of the rack storage. In this case, the fire propagates slightly faster than in scenarios W.2.1 and W.2.2 due to the central ignition of fire in the building. As in previous cases, the natural smoke extraction flow is not enough to effectively evacuate the heat generated by the fire.

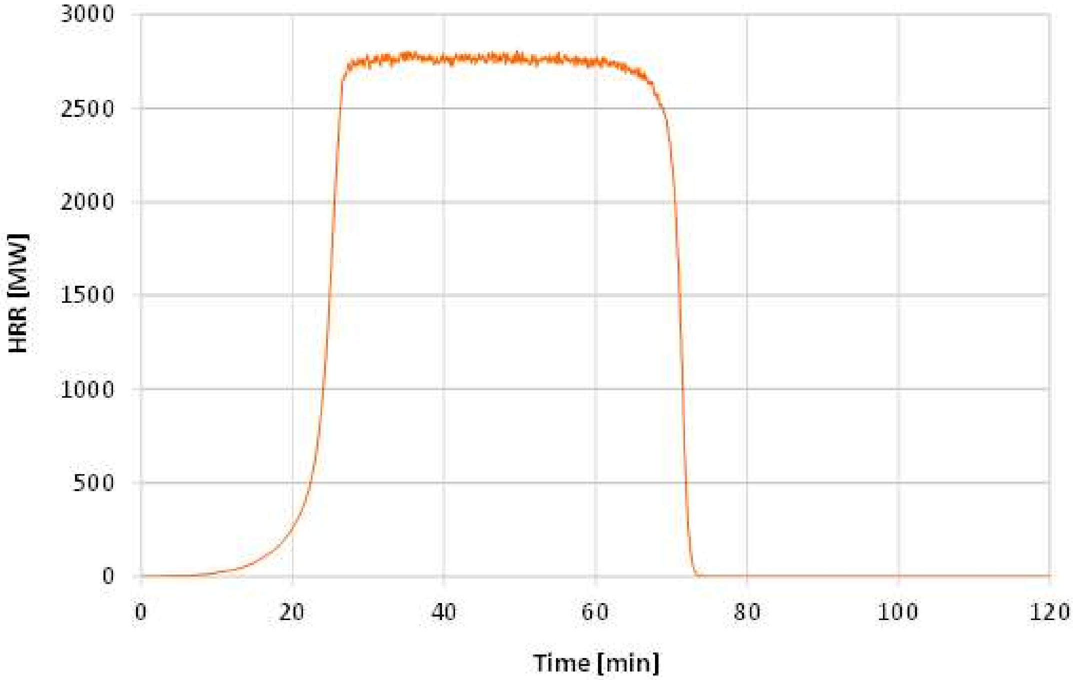
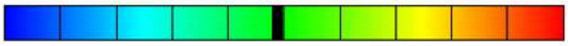
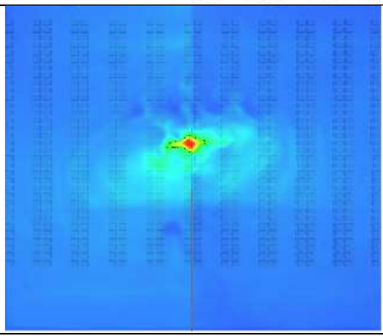
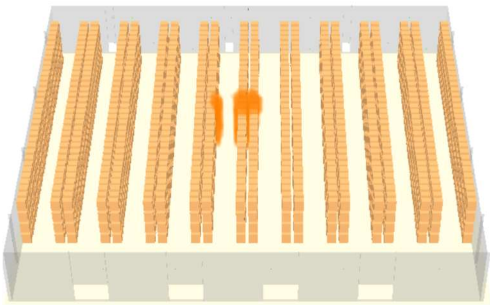
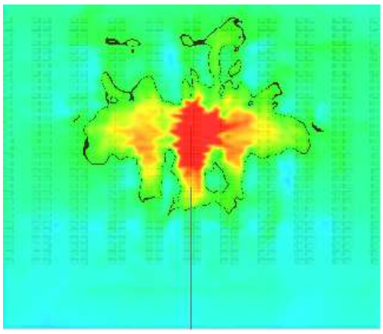
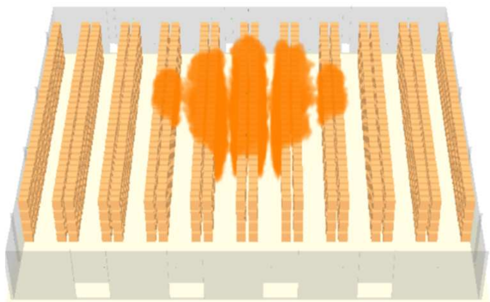
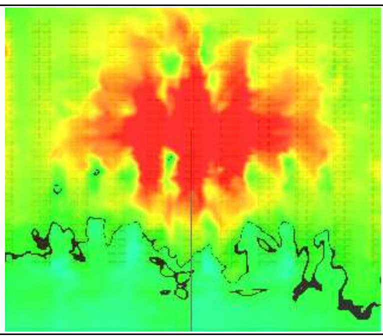
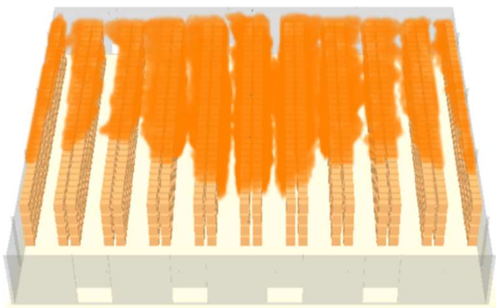


Figure 110: HRR calculated for the scenario W.2.3

	
	
(a) Plan view 1m under the roof at 10 minutes	(b) Pallets involved in fire at 10 minutes
	
(c) Plan view 1m under the roof at 20 minutes	(d) Pallets involved in fire at 20 minutes
	

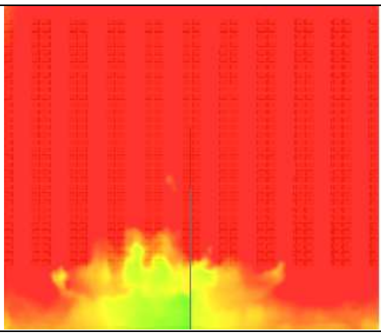
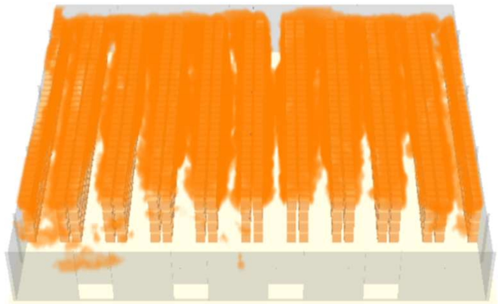
(e) Plan view 1m under the roof at 23 minutes	(f) Pallets involved in fire at 23 minutes
	
(g) Plan view 1m under the roof at 25 minutes	(h) Pallets involved in fire at 25 minutes

Figure 111: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 112 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 113). Gas temperatures reach 1000°C at 10 minutes above the ignition position. At 25 minutes, 1000°C gas temperature is obtained for almost the whole surface of the warehouse at 9 m height (Figure 111g).

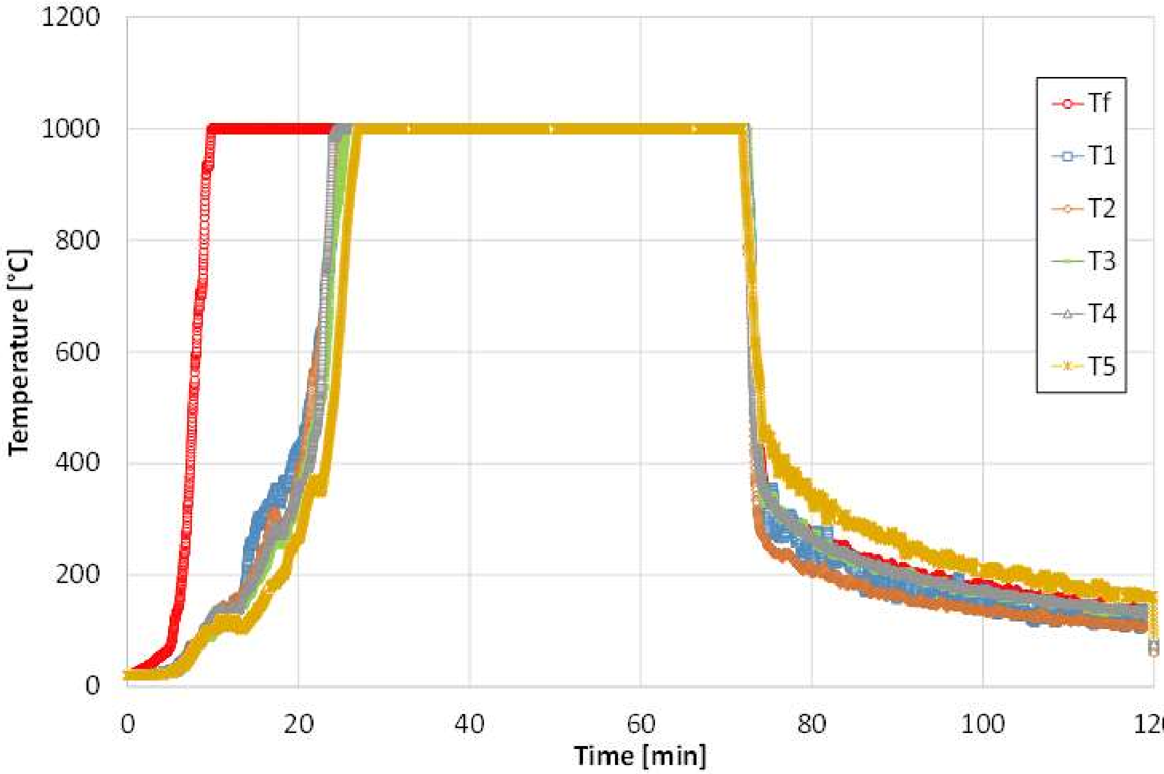


Figure 112: Gas temperature at different locations under the roof

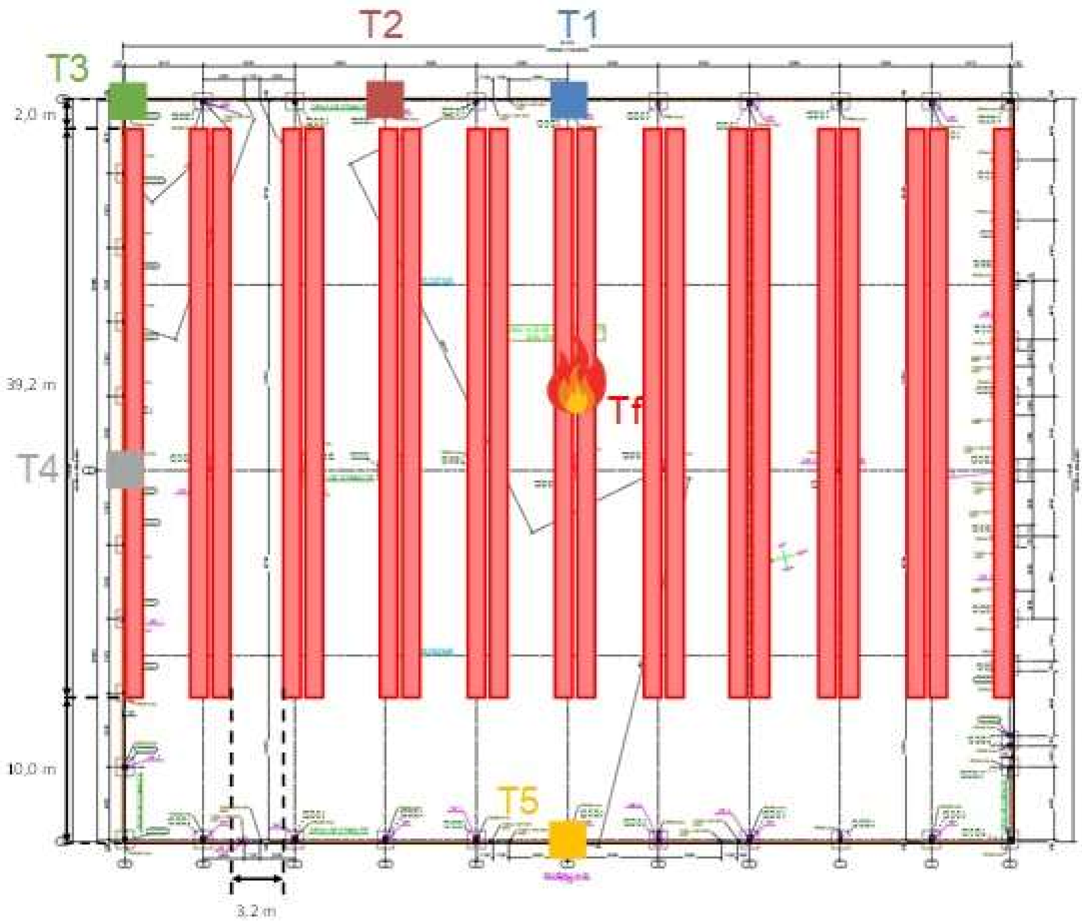


Figure 113: Temperature measurement point locations

Gas temperatures versus time at different heights along the column at position T1 are shown in Figure 108. The gas temperature increases more slowly at the lower parts during the first 25 minutes. However, high gas temperatures are observed in almost all the volume of the building after 30 minutes.

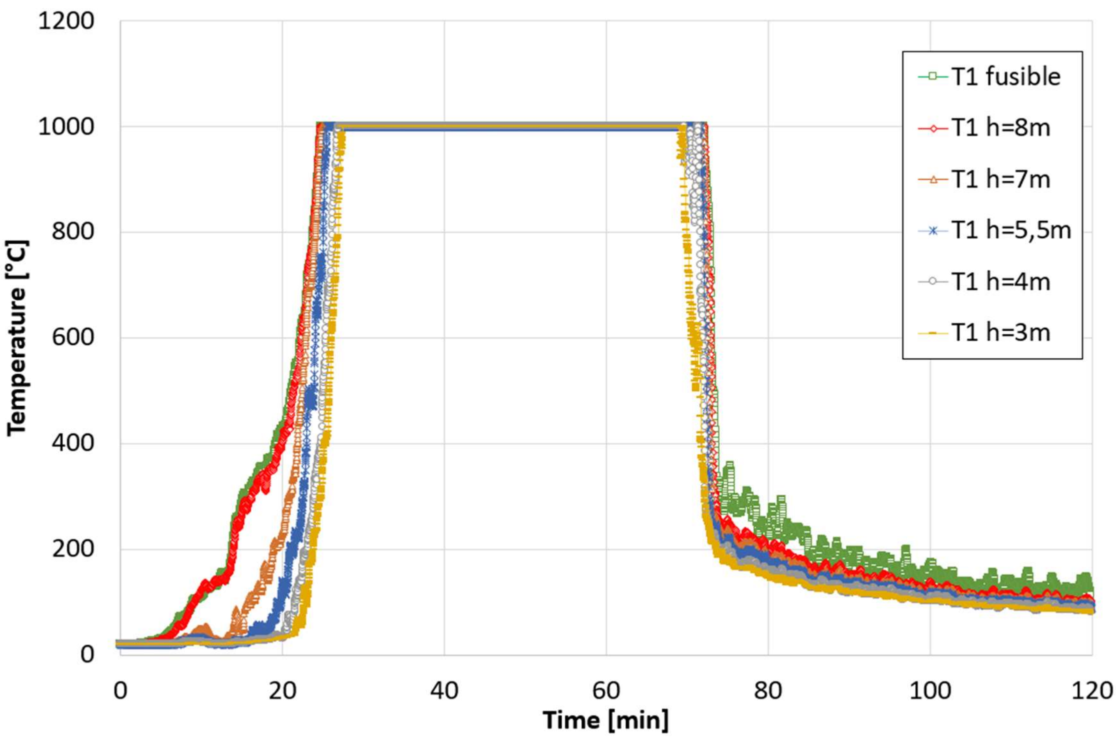
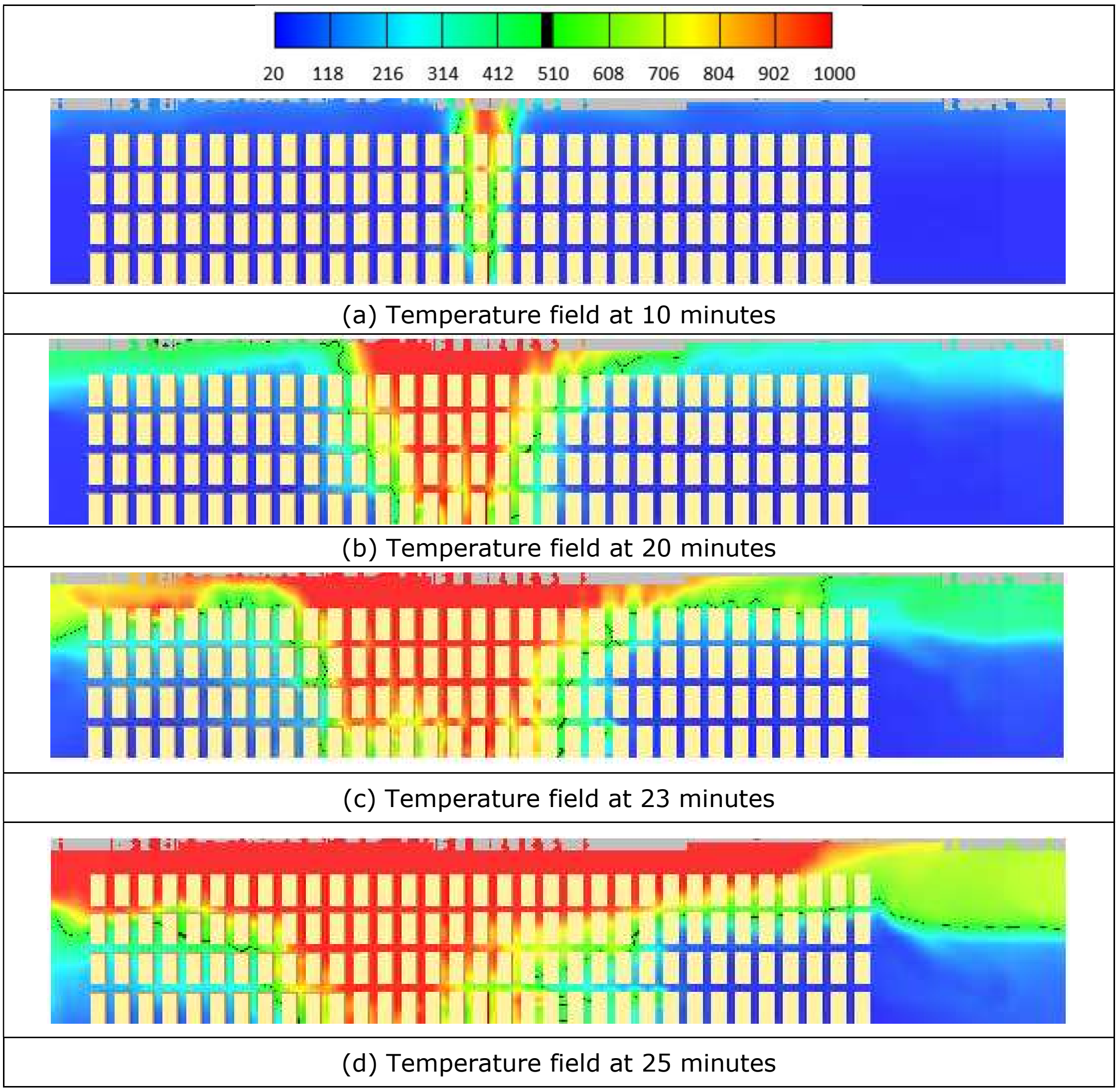


Figure 114: Gas temperatures versus time along the wall height at the location of thermocouple T1



(a) Temperature field at 10 minutes

(b) Temperature field at 20 minutes

(c) Temperature field at 23 minutes

(d) Temperature field at 25 minutes

Figure 115: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.10. Scenario S.2.1

This scenario concerns a 3100m² supermarket with a shelf storage system. The source of fire is situated at the end of a central double row shelf.

The calculated HRR is shown in Figure 116. The plan views in Figure 117 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. The fire slowly propagates along the shelves (Figure 117), resulting in moderate temperatures under the roof, of about 500°C.

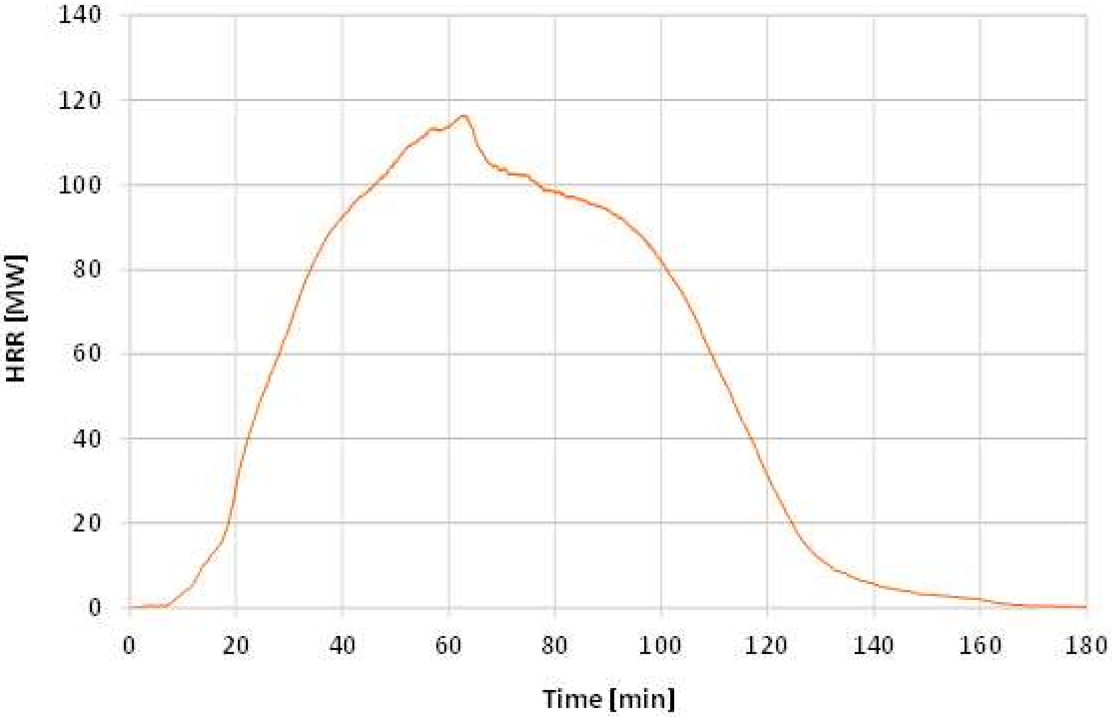
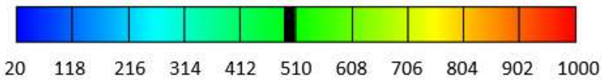
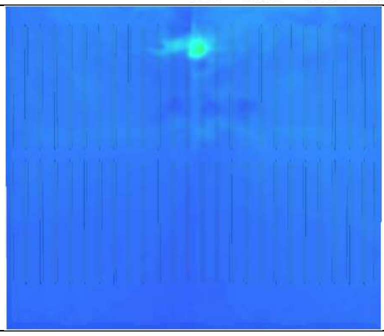
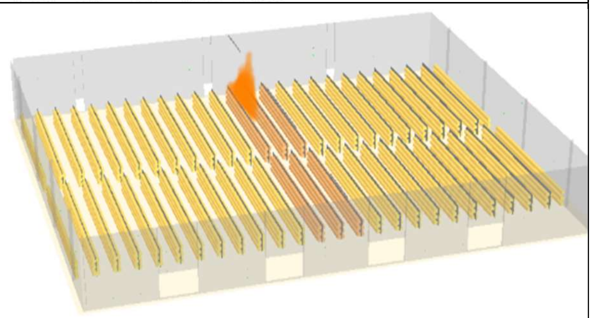
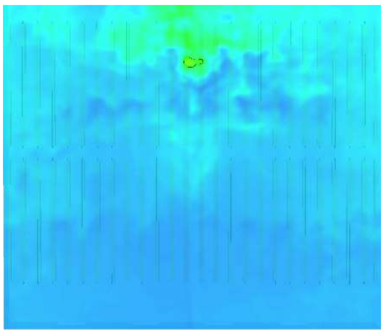
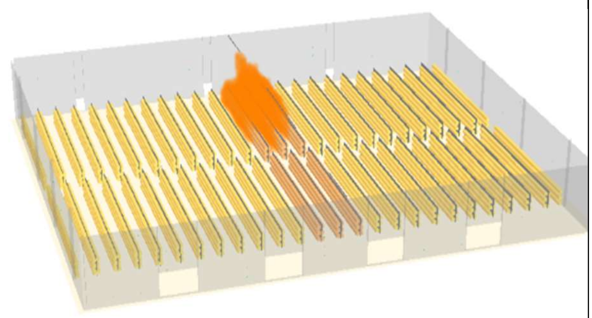
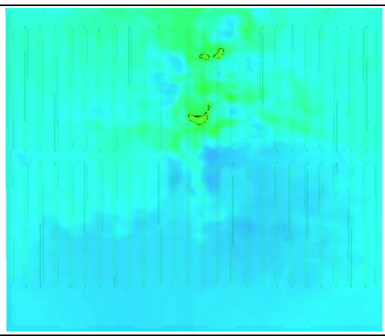
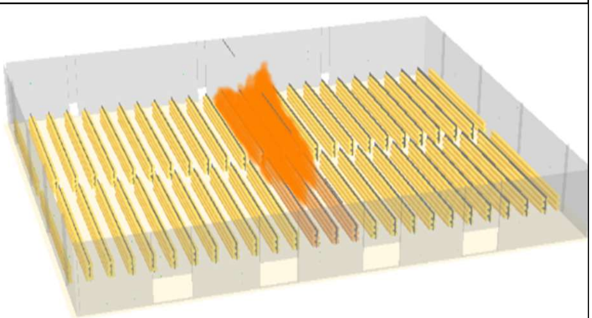


Figure 116: HRR calculated for the scenario S.2.1

	
	
(a) Plan view 1m under the roof at 15 minutes	(b) Pallets involved in fire at 15 minutes
	
(c) Plan view 1m under the roof at 30 minutes	(d) Pallets involved in fire at 30 minutes
	

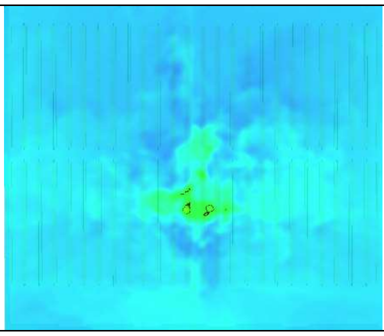
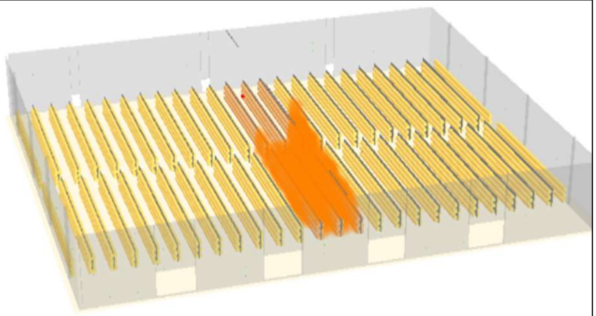
(e) Plan view 1m under the roof at 60 minutes	(f) Pallets involved in fire at 60 minutes
	
(g) Plan view 1m under the roof at 90 minutes	(h) Pallets involved in fire at 90 minutes

Figure 117: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 118 shows the gas temperatures calculated at 1m under the roof directly above location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 119). Maximum gas temperatures are about 500°C. These moderate temperatures are due to the high distance between the top of the shelf storage and the roof, and the large volume of the building.

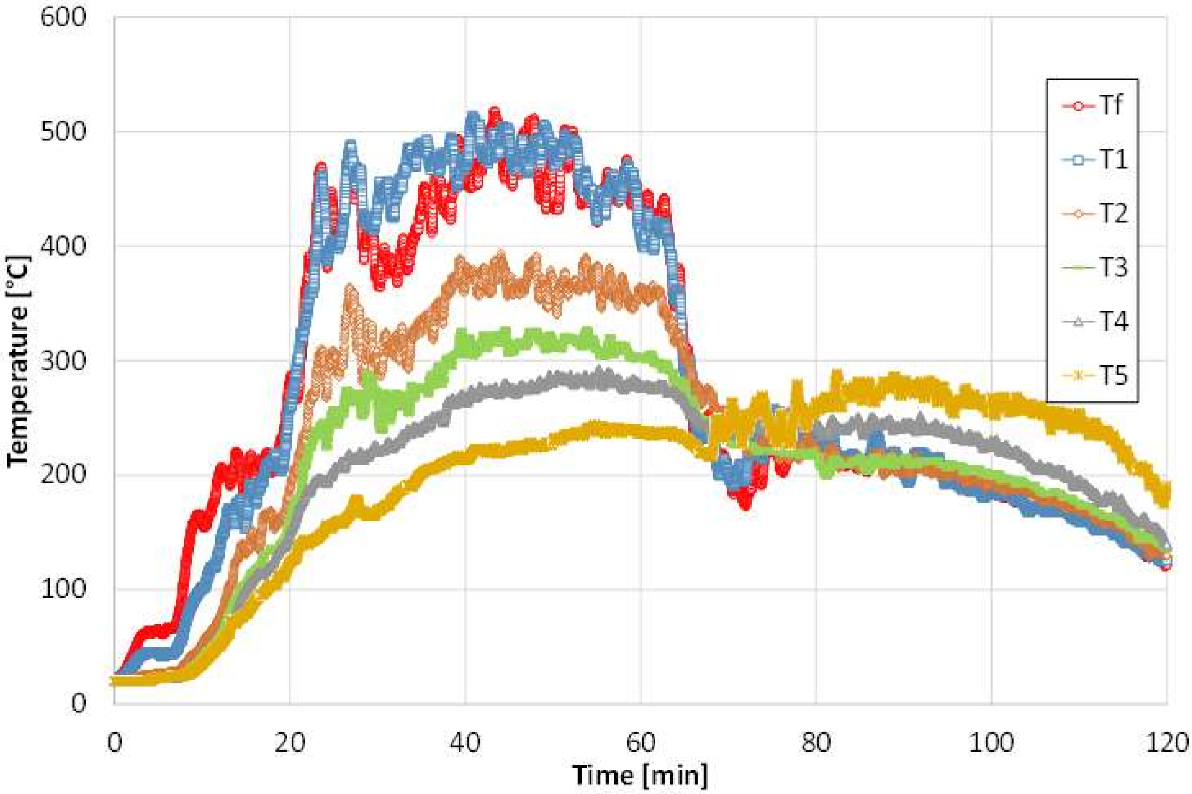


Figure 118: Gas temperature at different locations under the roof

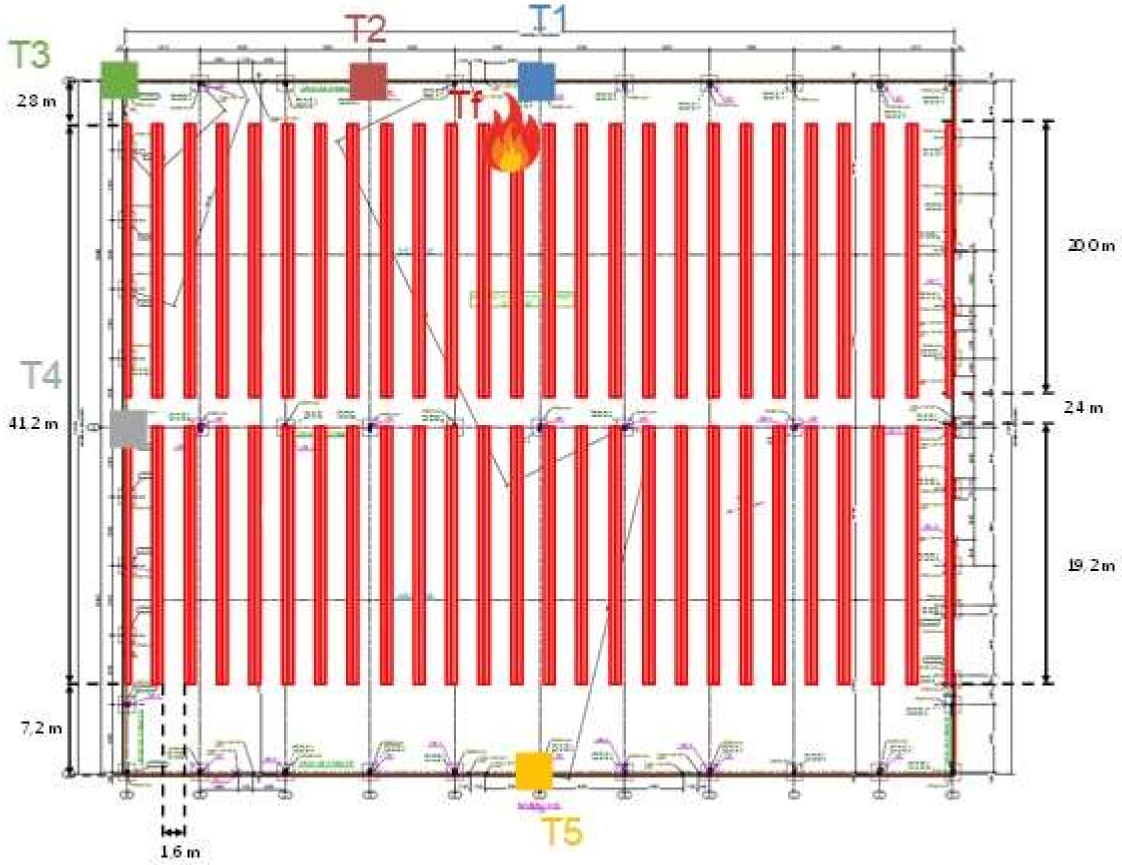


Figure 119: Temperature measurement point locations

Gas temperatures calculated at different wall heights nearest the fire source, at the same location as thermocouple T1, are shown in Figure 120. It can be noted that the gas temperatures are higher at the roof level and increase more slowly at the lower parts.

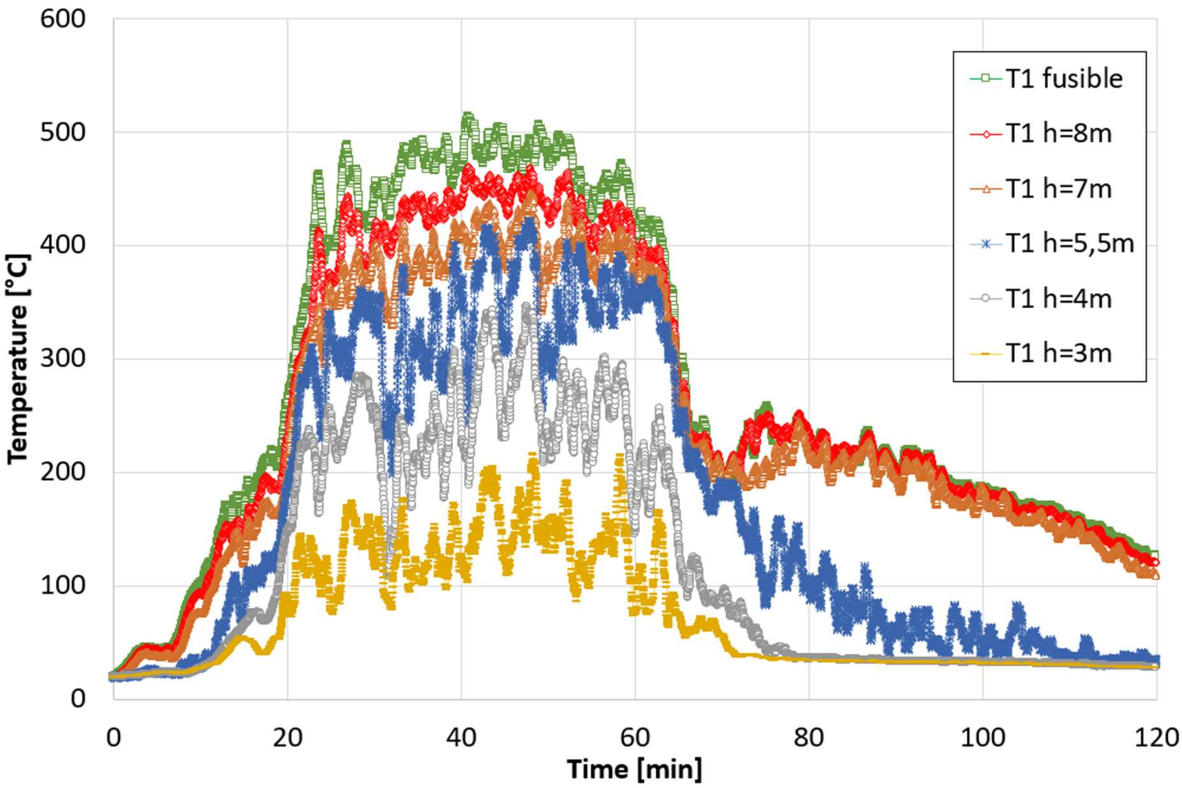
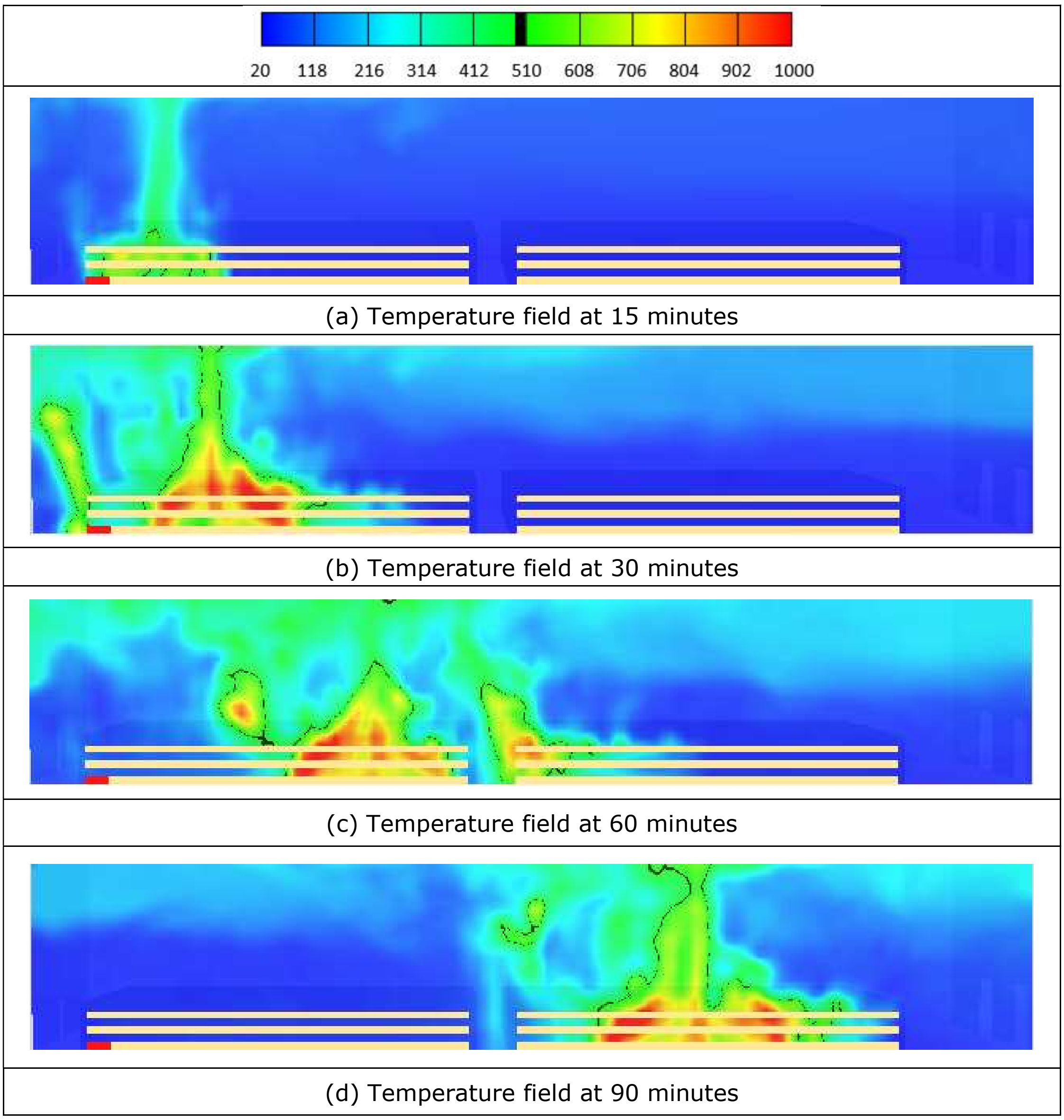


Figure 120: Gas temperatures vs time along the wall height at the location of thermocouple T1



(a) Temperature field at 15 minutes

(b) Temperature field at 30 minutes

(c) Temperature field at 60 minutes

(d) Temperature field at 90 minutes

Figure 121: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.11. Scenario S.2.2

This scenario concerns a 3100m² supermarket with a shelf storage system. The source of fire is situated in the middle of a single row shelf, near one of the shorter building walls.

The calculated HRR is shown in Figure 122. The plan views in Figure 123 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. In this scenario, the fire slowly propagates along the shelves. All the shelves storage to be involved in the fire are burning at approximately 50 minutes (see Figure 123f).

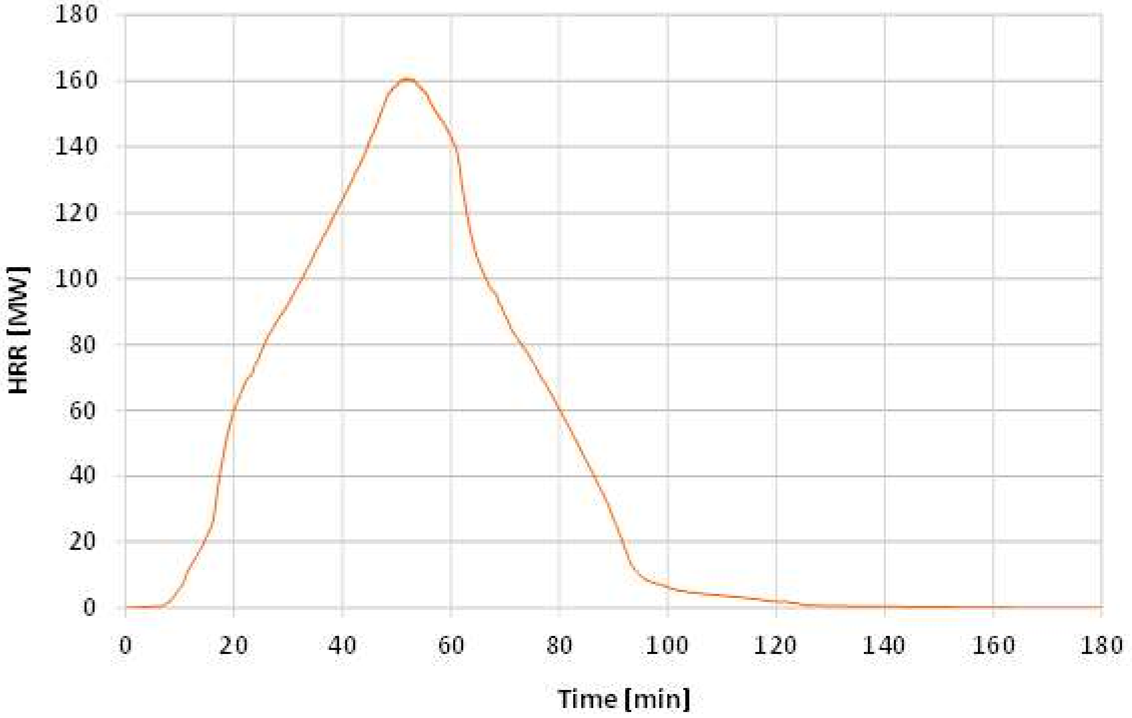
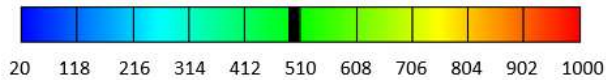
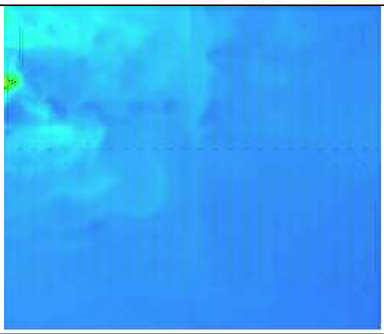
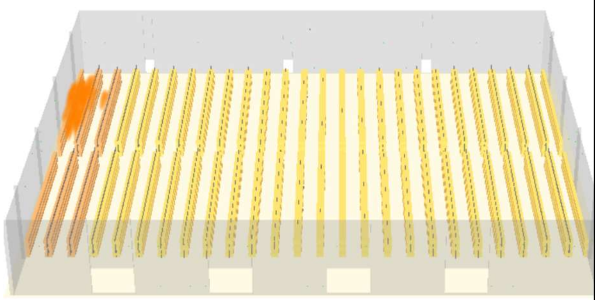


Figure 122: HRR calculated for the scenario S.2.2

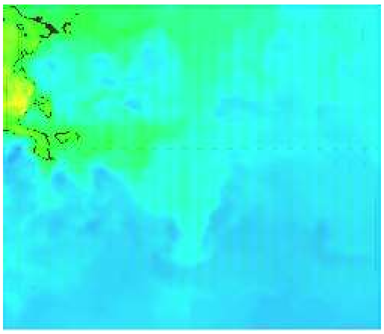




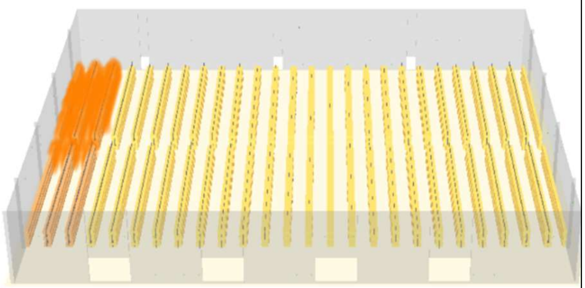
(a) Plan view 1m under the roof at 15 minutes



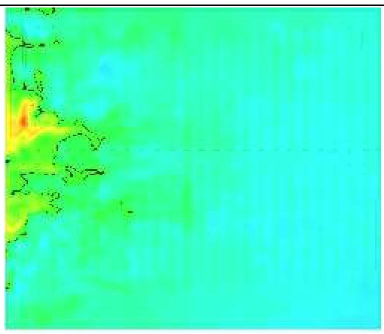
(b) Pallets involved in fire at 15 minutes

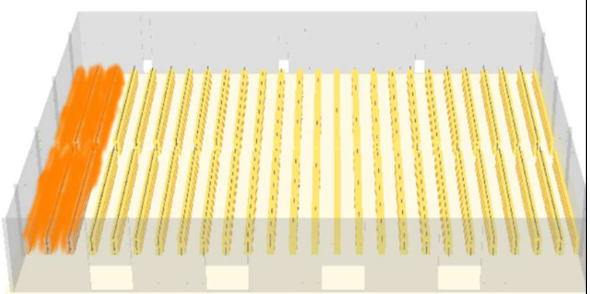


(c) Plan view 1m under the roof at 30 minutes



(d) Pallets involved in fire at 30 minutes





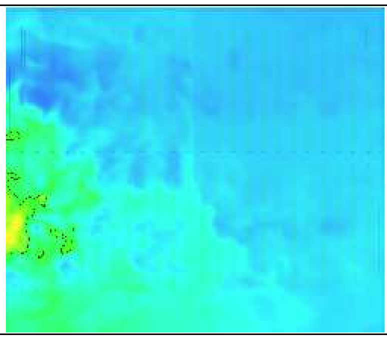
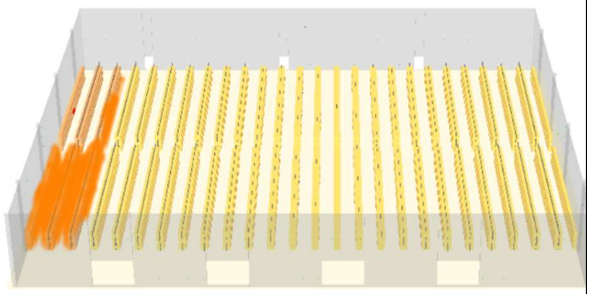
(e) Plan view 1m under the roof at 50 minutes	(f) Pallets involved in fire at 50 minutes
	
(g) Plan view 1m under the roof at 70 minutes	(h) Pallets involved in fire at 70 minutes

Figure 123: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 124 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 125). Maximum gas temperatures are about 700°C. The temperatures are higher than in the previous case (scenario W.2.1) because the fire ignition is located near a wall, resulting in more heat accumulation under the roof.

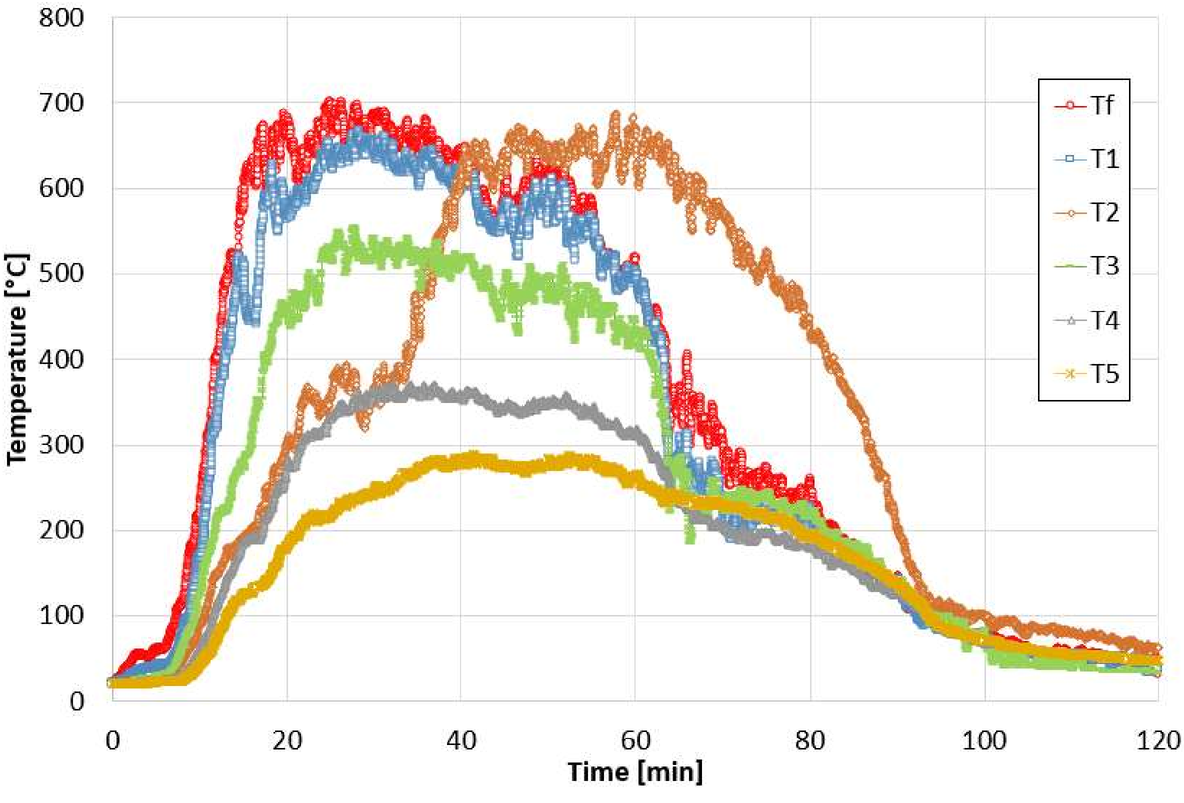


Figure 124: Gas temperature at different locations under the roof

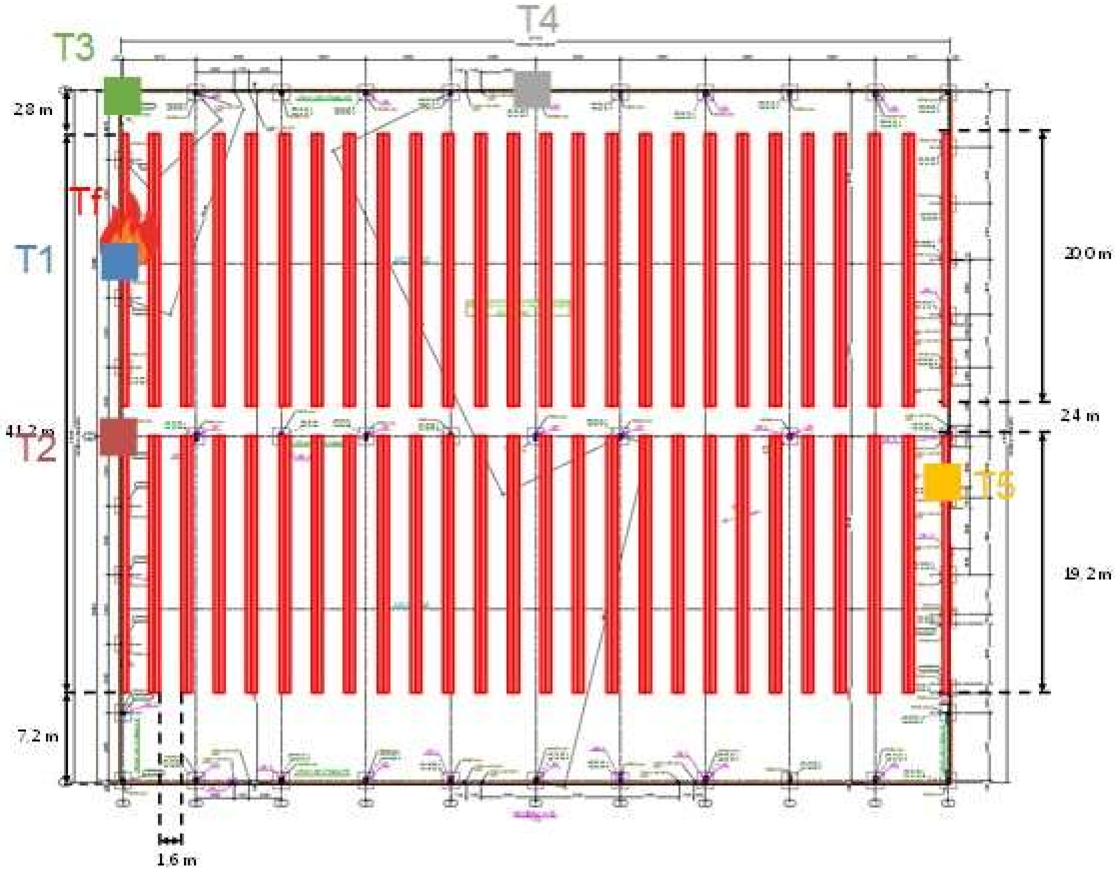


Figure 125: Temperature measurement point locations

Gas temperatures calculated at different wall heights nearest the fire source, at the same location as thermocouple, T1 are shown in Figure 126. Since the thermocouple is located near the ignition position, temperature increases quickly and uniformely along the height.

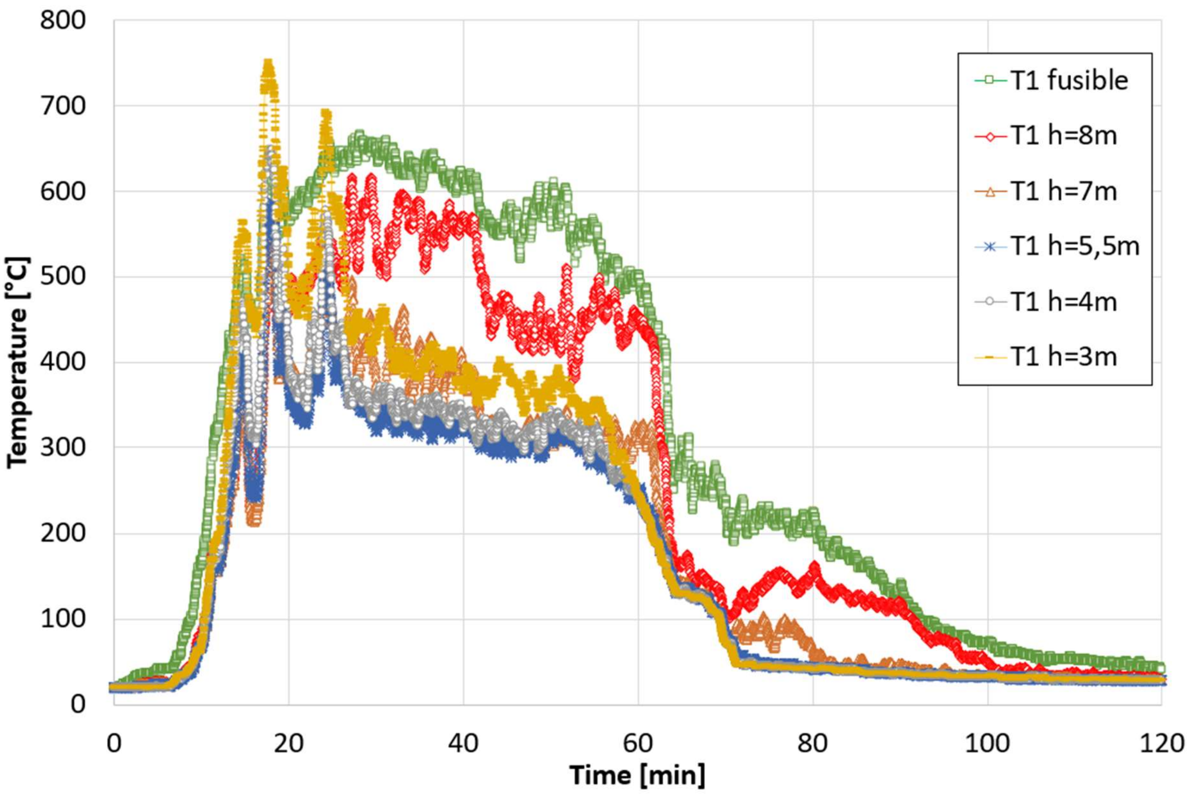
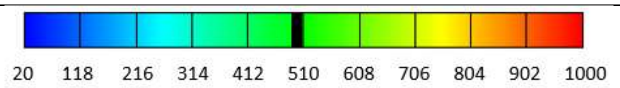
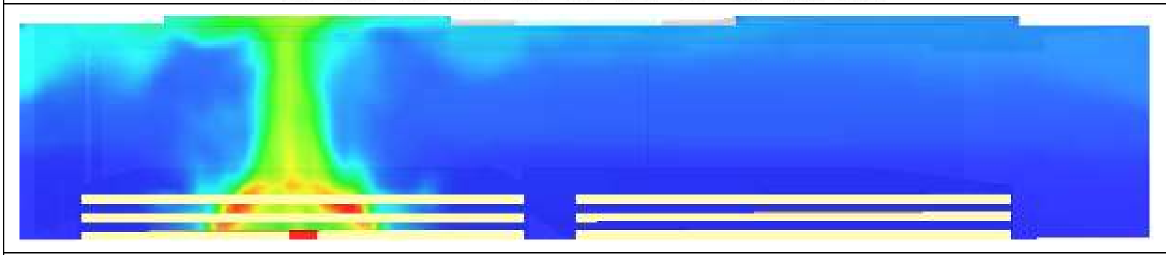
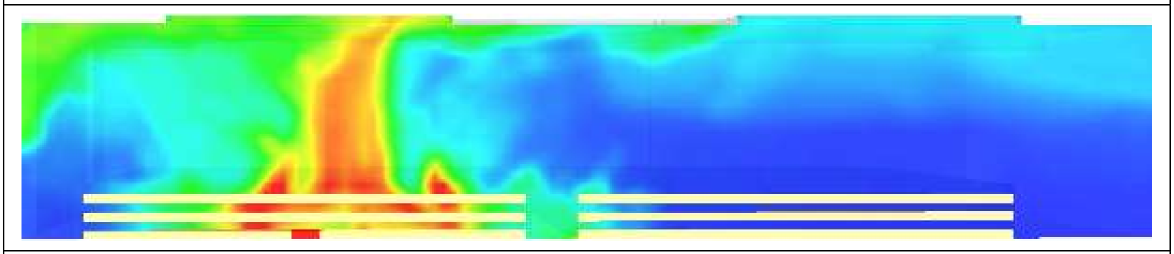


Figure 126: Gas temperatures vs time along the wall height at the location of thermocouple T1

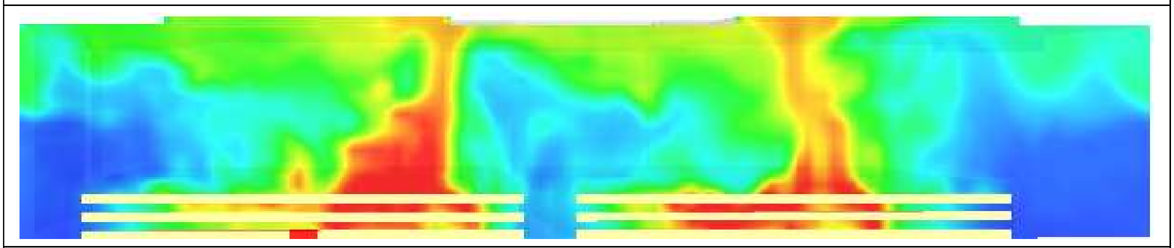




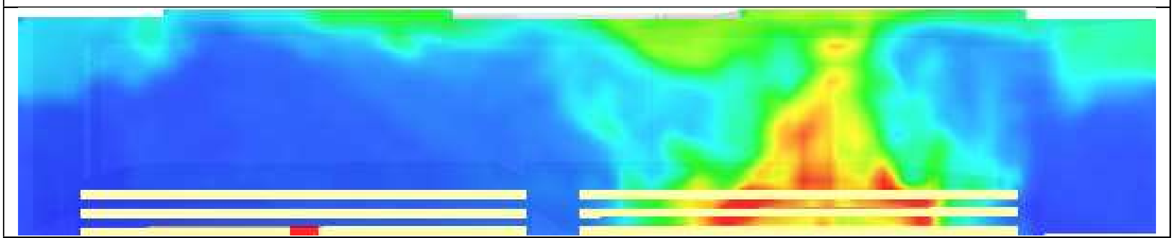
(a) Temperature field at 15 minutes



(b) Temperature field at 30 minutes



(c) Temperature field at 50 minutes



(d) Temperature field at 70 minutes

Figure 127: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.12. Scenario S.2.3

This scenario concerns a 3100m² supermarket with a shelf storage system. The source of fire is situated in the middle of central double-row shelves.

The calculated HRR is shown in Figure 128. The plan views in Figure 129 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. In this scenario, the fire slowly propagates along the storage (Figure 129), resulting in moderate temperatures under the roof, of about 500°C.

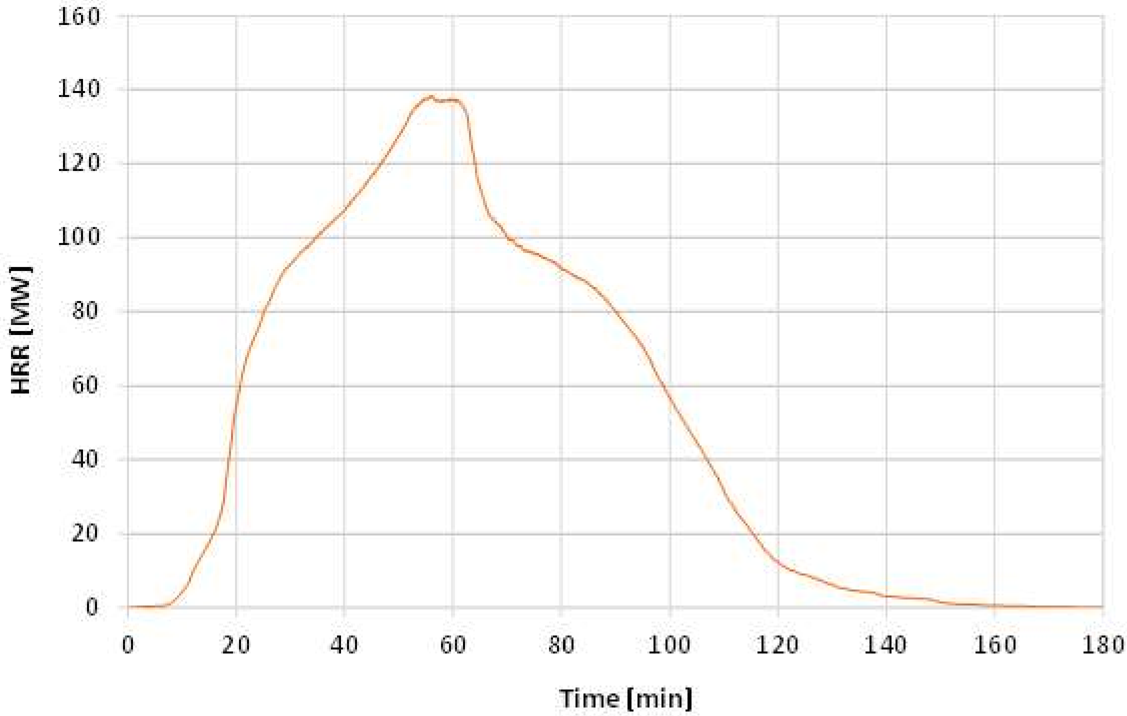
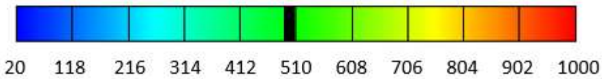
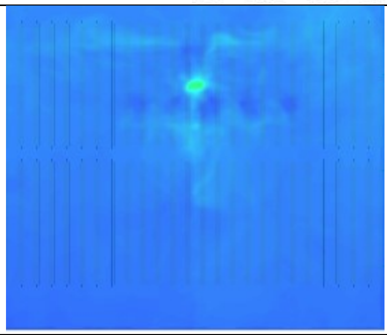
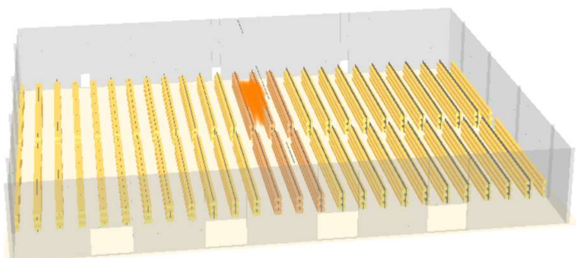
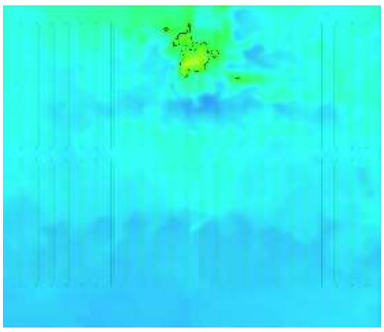
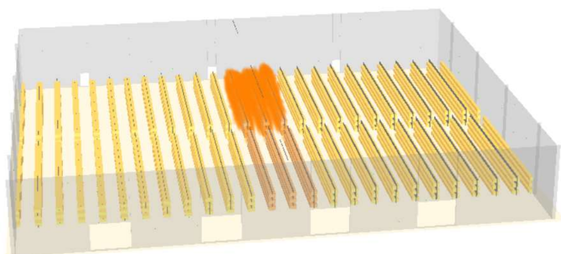
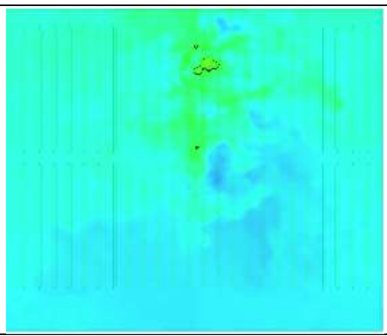
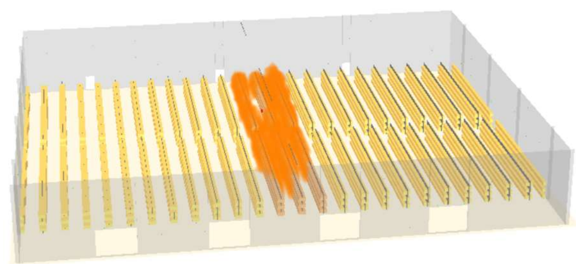


Figure 128: HRR calculated for the scenario S.2.3



	
(a) Plan view 1m under the roof at 15 minutes	(b) Pallets involved in fire at 15 minutes
	
(c) Plan view 1m under the roof at 30 minutes	(d) Pallets involved in fire at 30 minutes
	

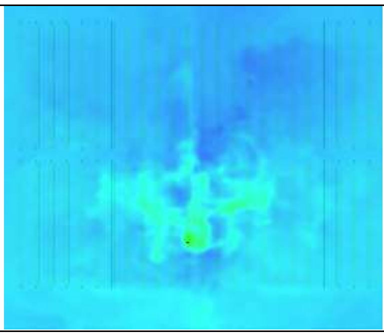
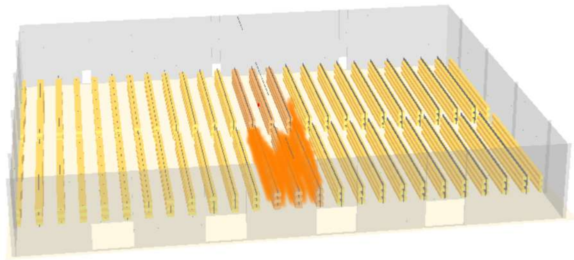
(e) Plan view 1m under the roof at 60 minutes	(f) Pallets involved in fire at 60 minutes
	
(g) Plan view 1m under the roof at 90 minutes	(h) Pallets involved in fire at 90 minutes

Figure 129: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 130 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 131). Maximum gas temperatures are about 500-600°C. These moderate temperatures are due to the high distance between the top of the shelf storage and the roof and the large volume of the building.

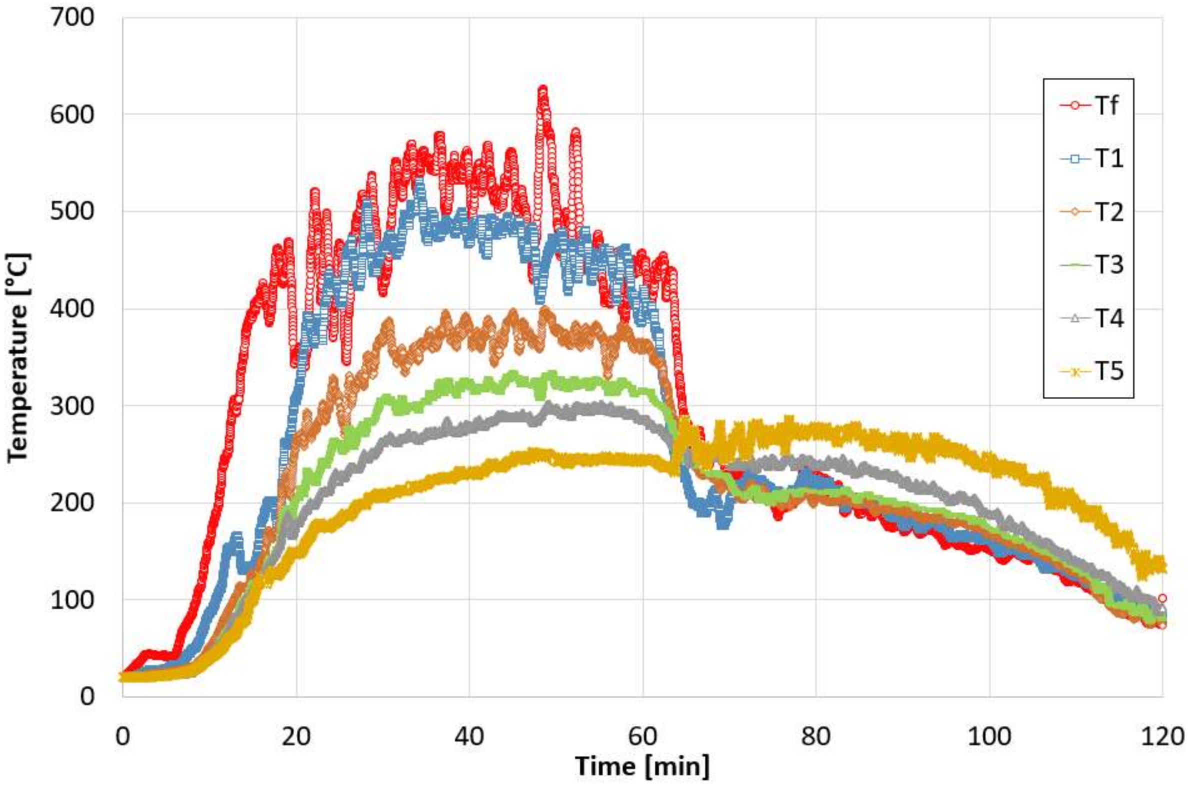


Figure 130: Gas temperature at different locations under the roof

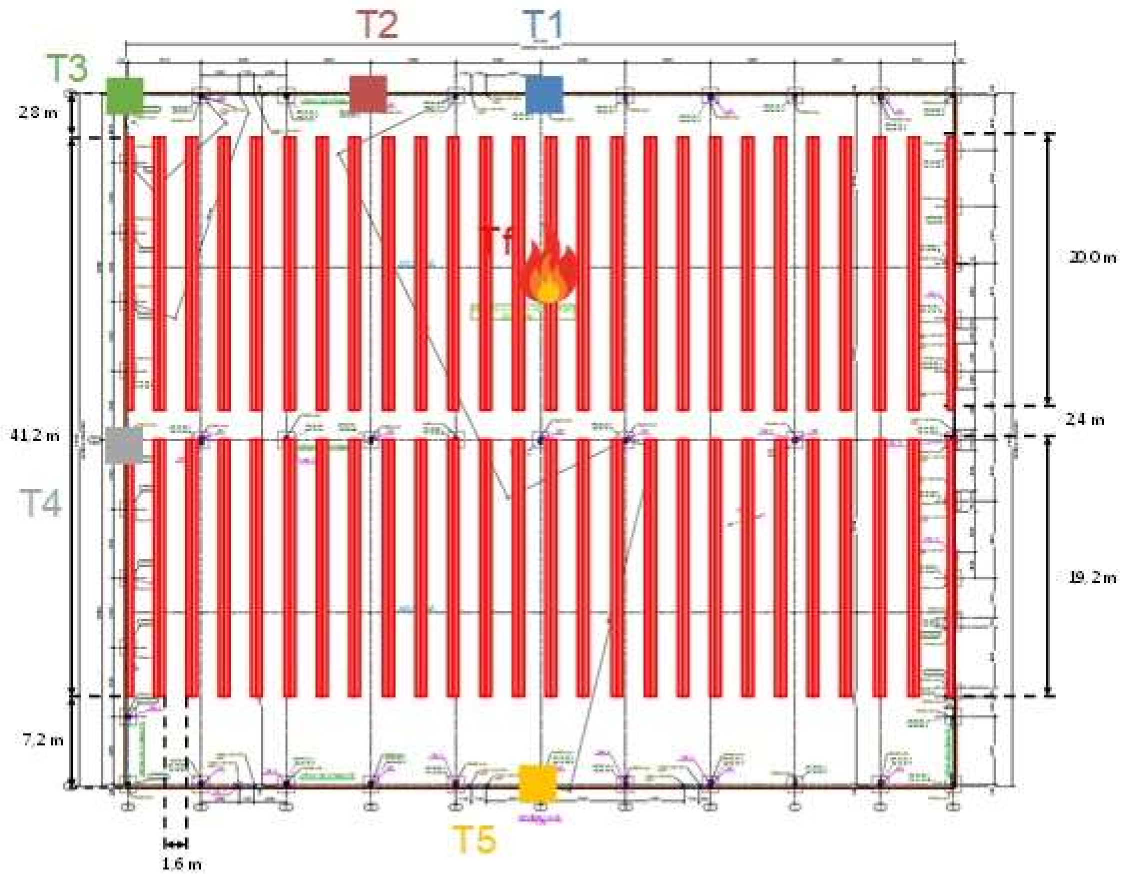


Figure 131: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple, T1 are shown in Figure 132. The gas temperature increases more slowly at the lower parts.

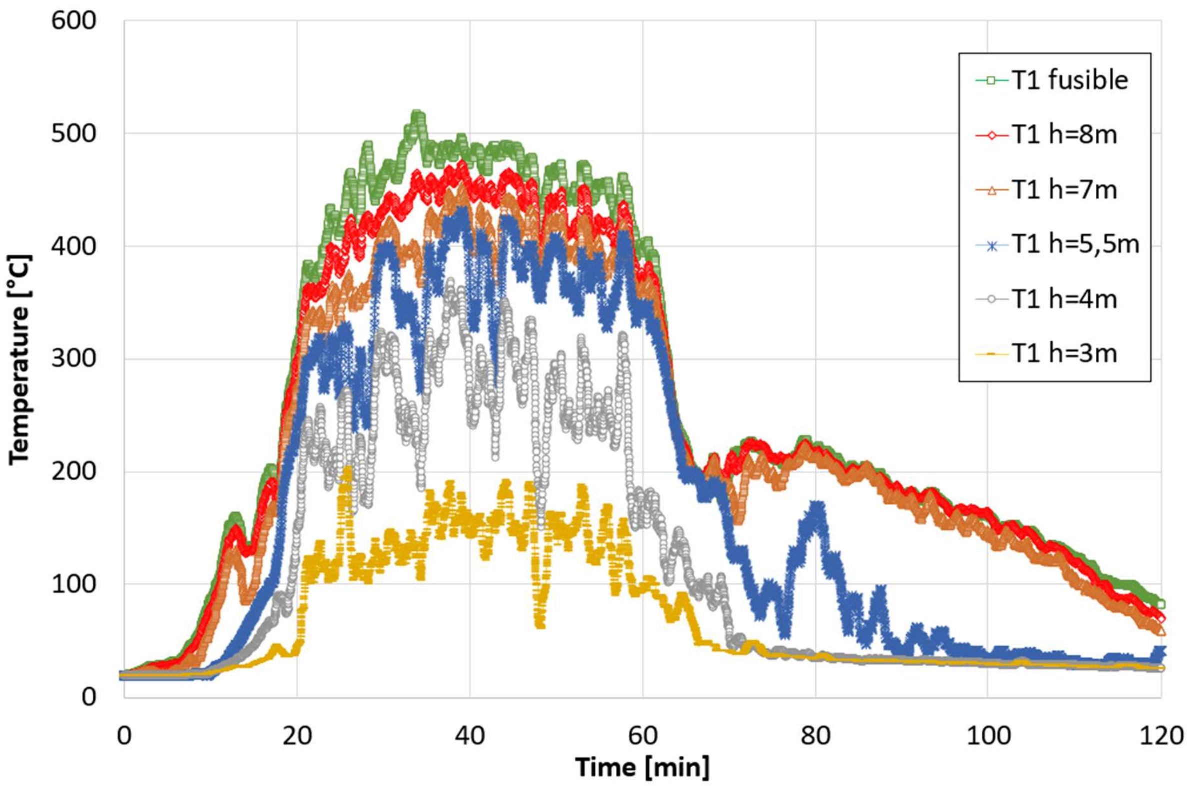
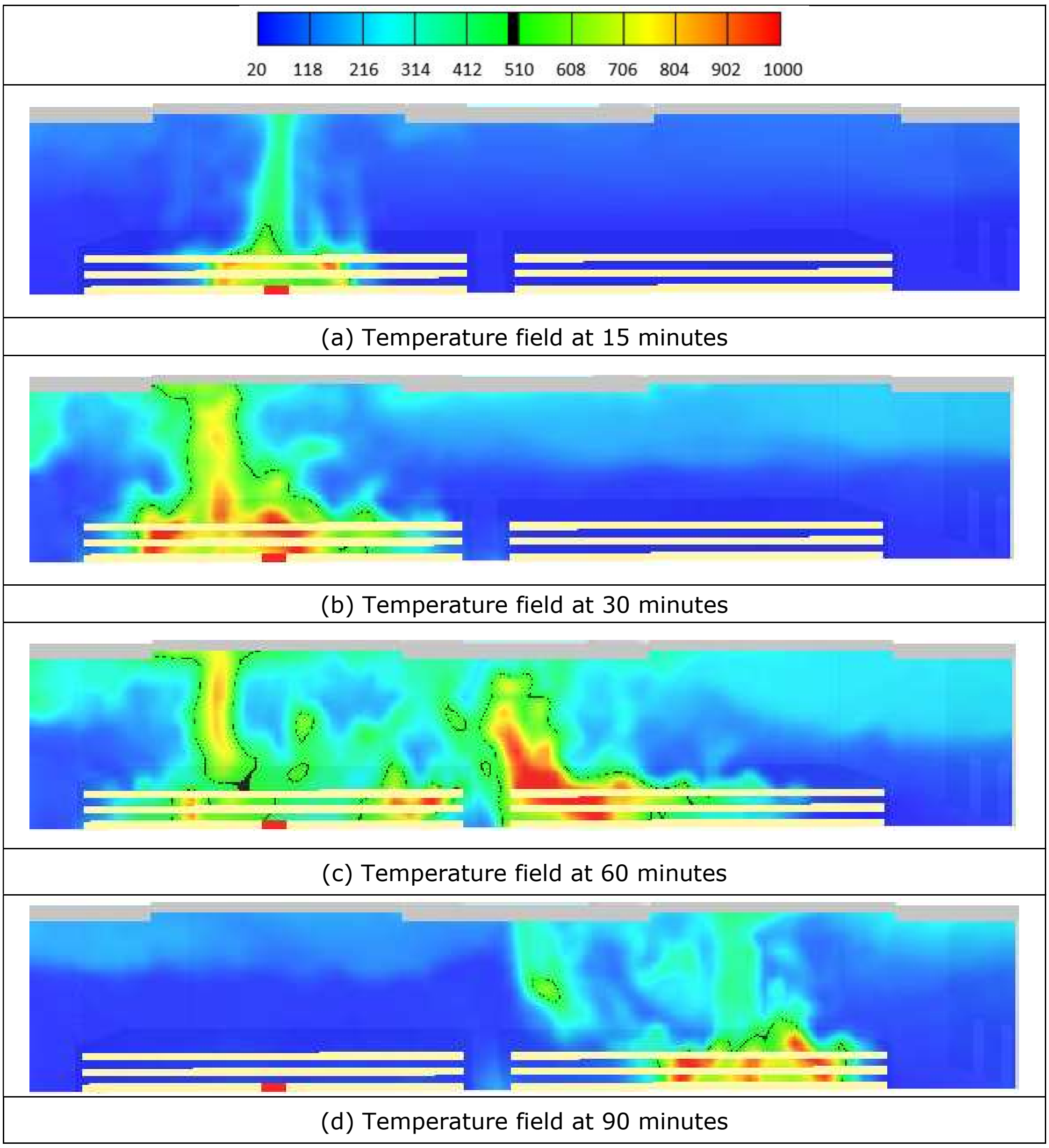


Figure 132: Gas temperatures vs time along the wall height at the location of thermocouple T1



(a) Temperature field at 15 minutes

(b) Temperature field at 30 minutes

(c) Temperature field at 60 minutes

(d) Temperature field at 90 minutes

Figure 133: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.13.Scenario I.2.1

This scenario concerns a 3100m² industrial building with a bulk storage, located near one of the longer building walls.

The calculated HRR is shown in Figure 134. The maximum HRR is about 30 MW. The plan views in Figure 135 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. Considering the large volume of the building, this fire can be considered as a "localized fire". The bulk storage is fully involved in fire at 20 minutes (Figure 135f). After 45 minutes, the fire decays due to a lack of combustible.

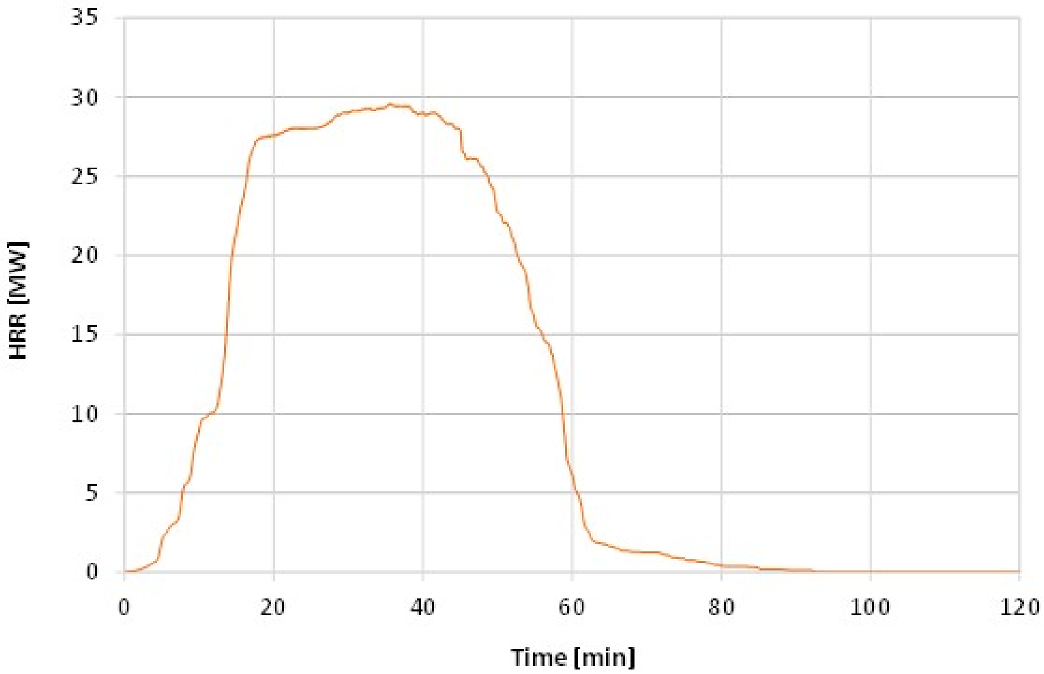
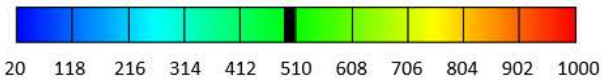
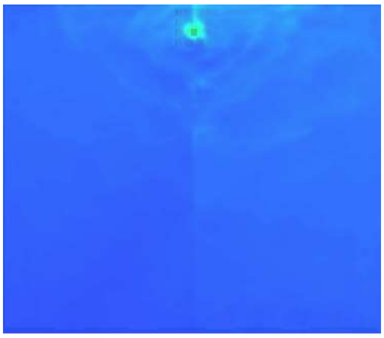
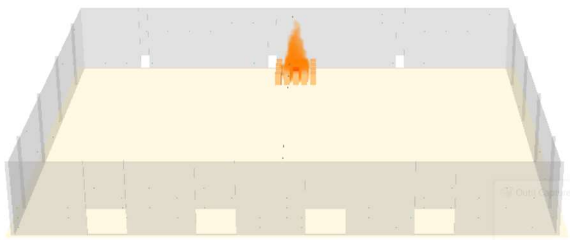
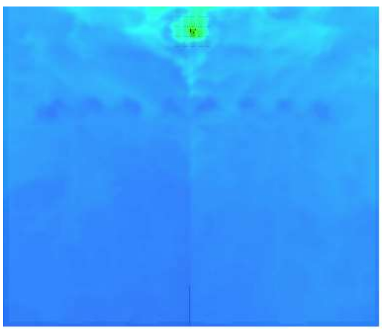
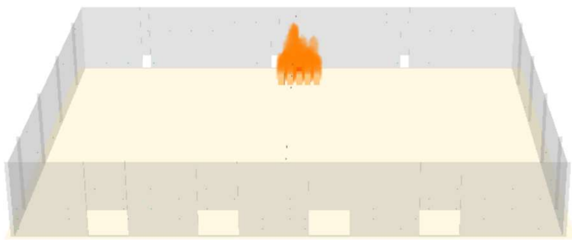
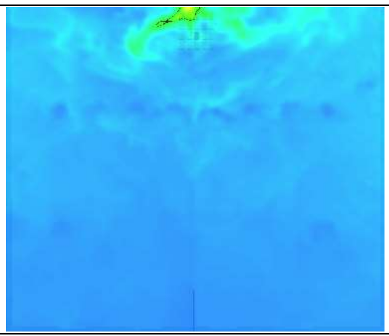
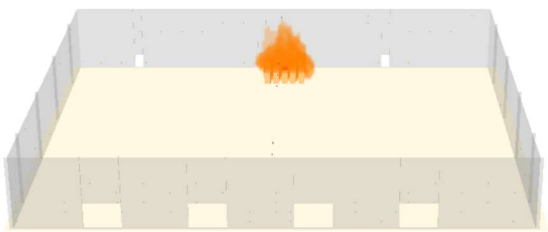


Figure 134: HRR calculated for the scenario I.2.1

	
	
(a) Plan view 1m under the roof at 10 minutes	(b) Pallets involved in fire at 10 minutes
	
(c) Plan view 1m under the roof at 15 minutes	(d) Pallets involved in fire at 15 minutes
	

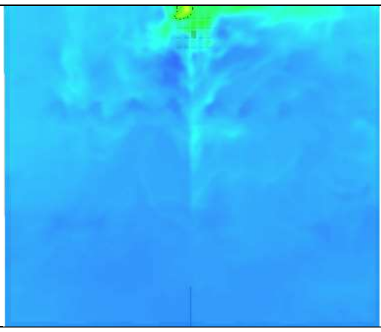
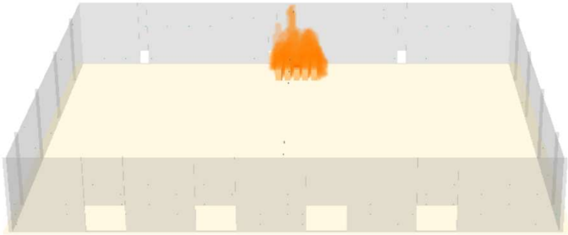
(e) Plan view 1m under the roof at 20 minutes	(f) Pallets involved in fire at 20 minutes
	
(g) Plan view 1m under the roof at 40 minutes	(h) Pallets involved in fire at 40 minutes

Figure 135: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 136 shows the gas temperatures calculated at 1m under the roof directly above the ignition position and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 137). Maximum gas temperature is about 600°C at thermocouple Tf, directly above the ignition position, and 700°C at thermocouple T1. The temperature is higher at thermocouple T1 because there is a heat accumulation under the roof near the wall.

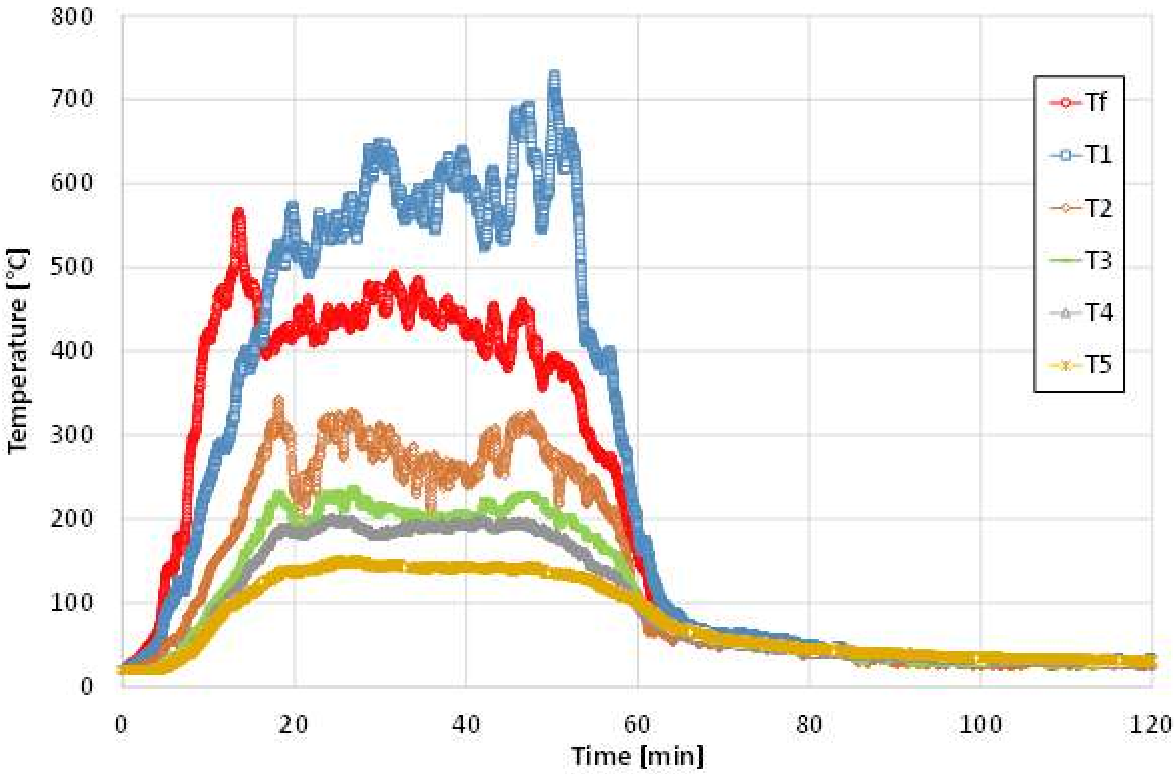


Figure 136: Gas temperature at different locations under the roof

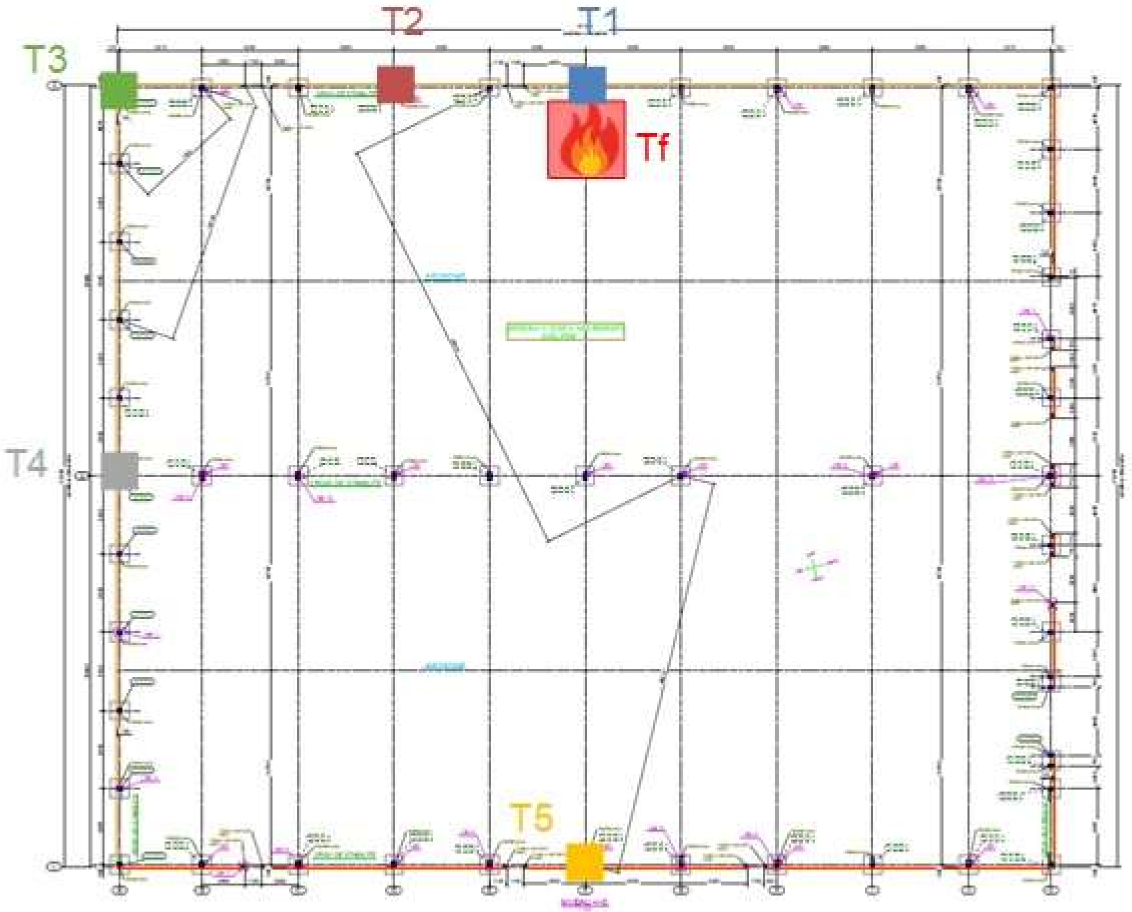


Figure 137: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple T1, are shown in Figure 138. It can be noted that higher temperatures are observed at the lower parts. This is due to the fire plume that is leaning against the wall (see Figure 139).

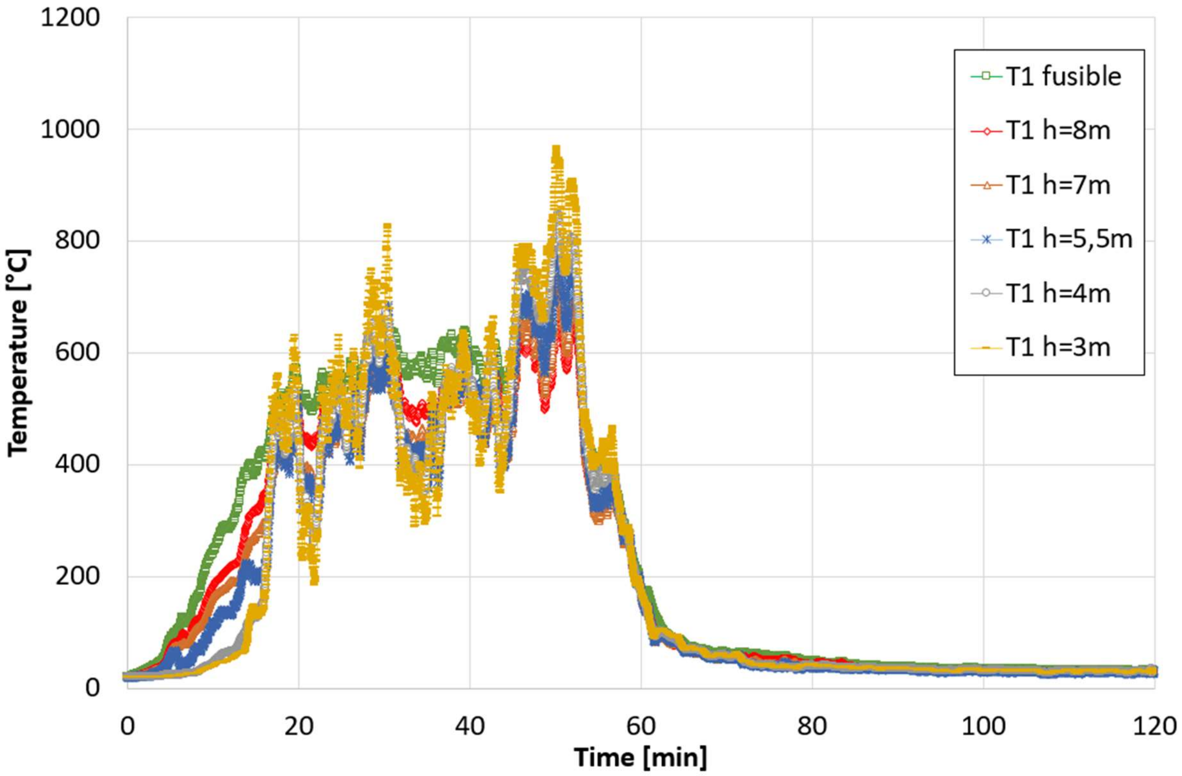
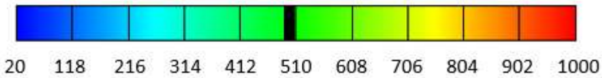
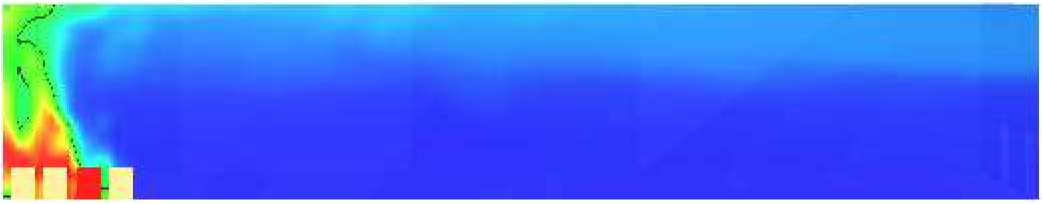


Figure 138: Gas temperatures vs time along the wall height at the location of thermocouple T1



(a) Temperature field at 10 minutes

(b) Temperature field at 15 minutes



(c) Temperature field at 20 minutes

(d) Temperature field at 40 minutes

Figure 139: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.14. Scenario I.2.2

This scenario concerns a 3100m² industrial building with a bulk storage, located near one of the shorter building walls.

The calculated HRR is shown in Figure 140. The maximum HRR is about 26 MW. The plan views in Figure 141 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. Considering the large volume of the warehouse, this fire can be considered as a “localized fire”. The bulk storage is fully involved in fire at 20 minutes (see Figure 141f).

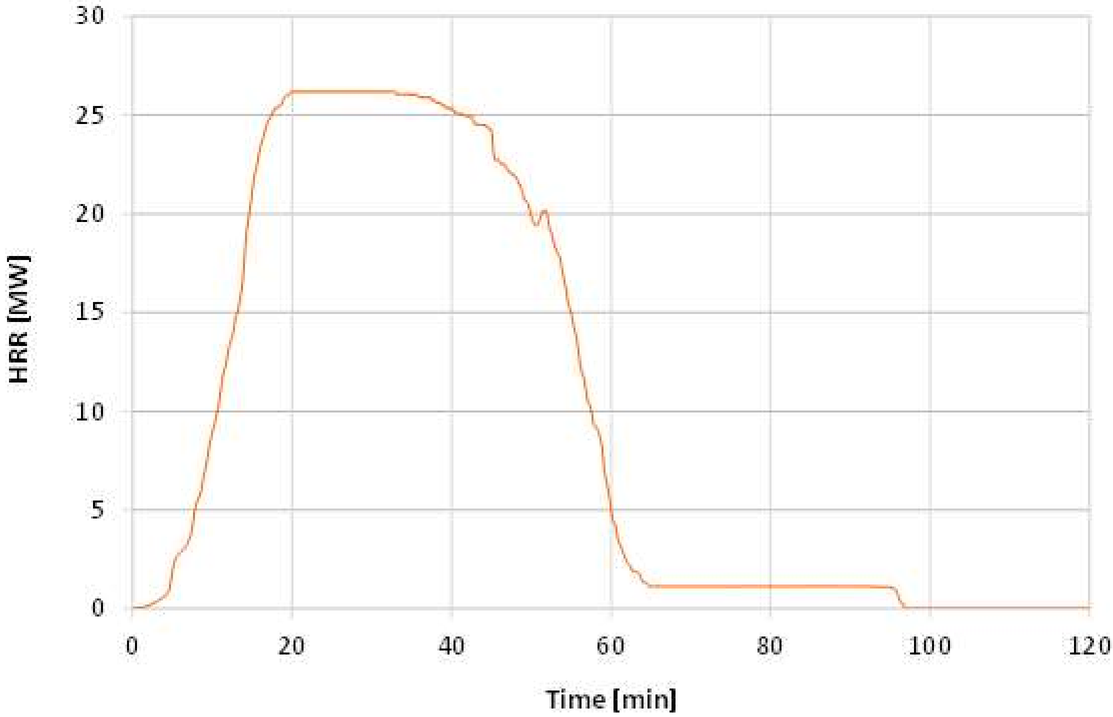
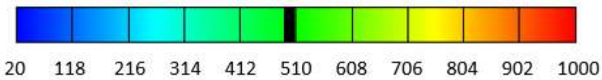
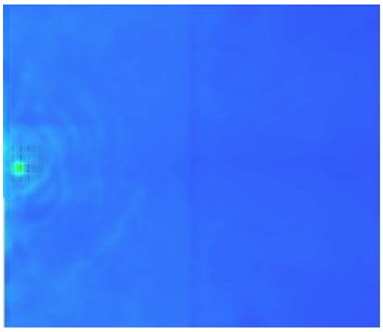
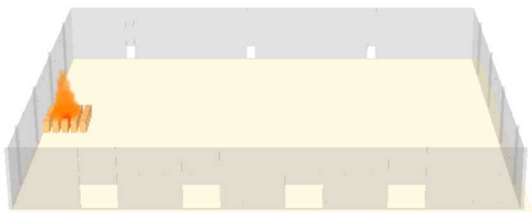
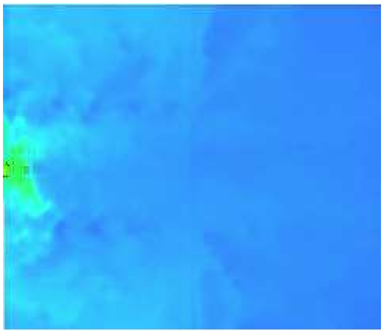
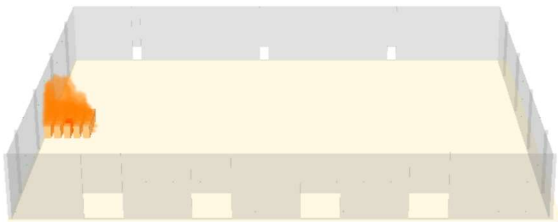


Figure 140: HRR calculated for the scenario I.2.2



	
(a) Plan view 1m under the roof at 10 minutes	(b) Pallets involved in fire at 10 minutes
	
(c) Plan view 1m under the roof at 15 minutes	(d) Pallets involved in fire at 15 minutes

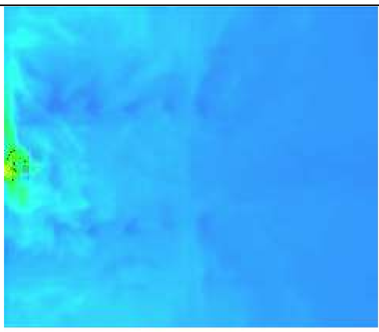
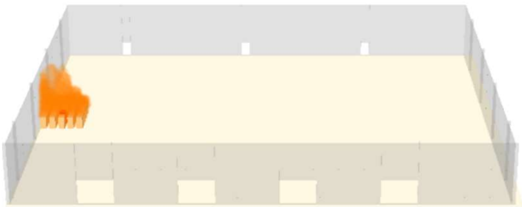
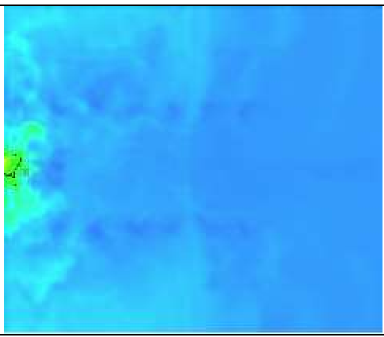
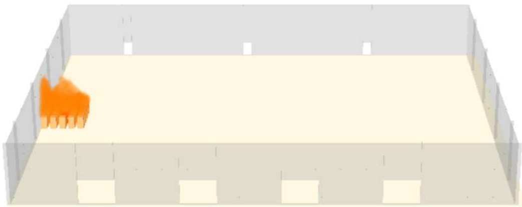
	
(e) Plan view 1m under the roof at 20 minutes	(f) Pallets involved in fire at 20 minutes
	
(g) Plan view 1m under the roof at 40 minutes	(h) Pallets involved in fire at 40 minutes

Figure 141: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 142 shows the gas temperatures calculated at 1m under the roof directly above the ignition position and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), close or far away from the fire source (as indicated in Figure 143). As the previous case, the maximum temperature is obtained at thermocouple T1 (with a peak of about 800°C).

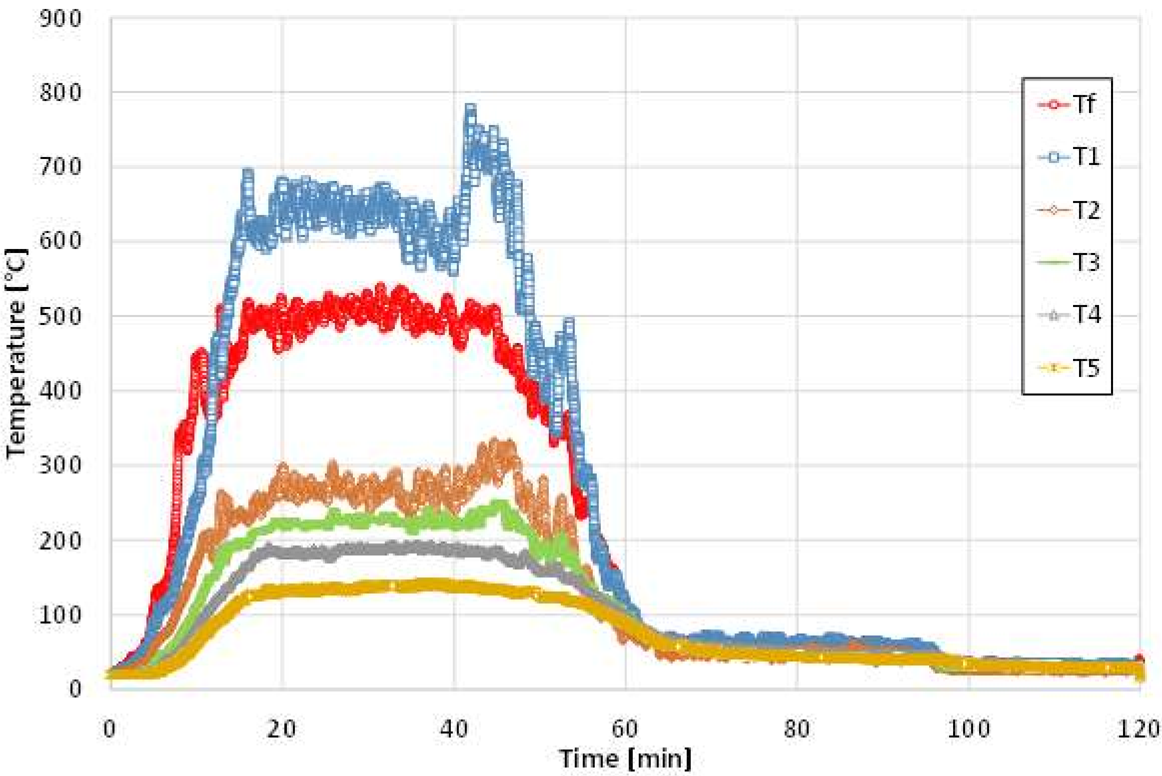


Figure 142: Gas temperature at different locations under the roof

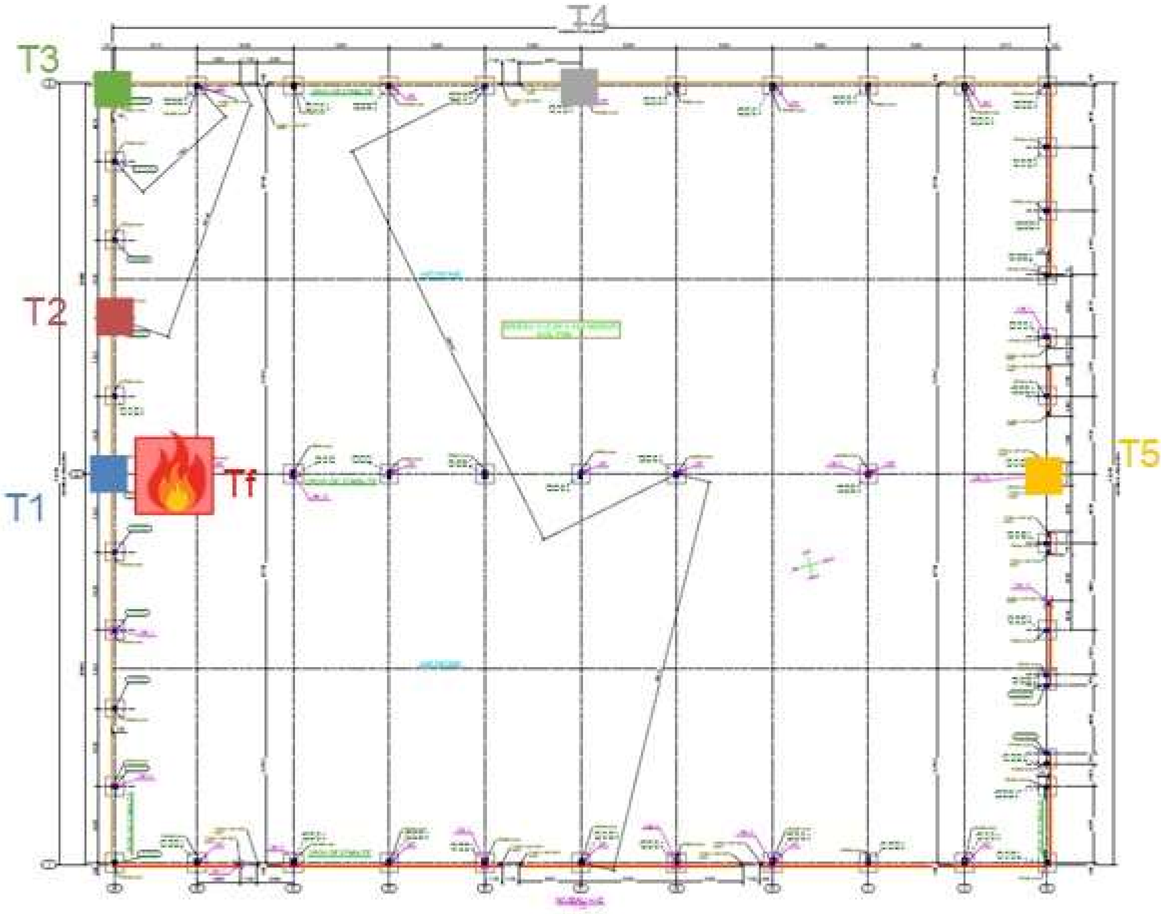


Figure 143: Temperature measurement point Locations

Gas temperatures at different wall heights nearest the fire source, at the same location as thermocouple, T1 are shown in Figure 144. Higher temperatures are observed at the lower parts due to the fire plume that is leaning against the wall.

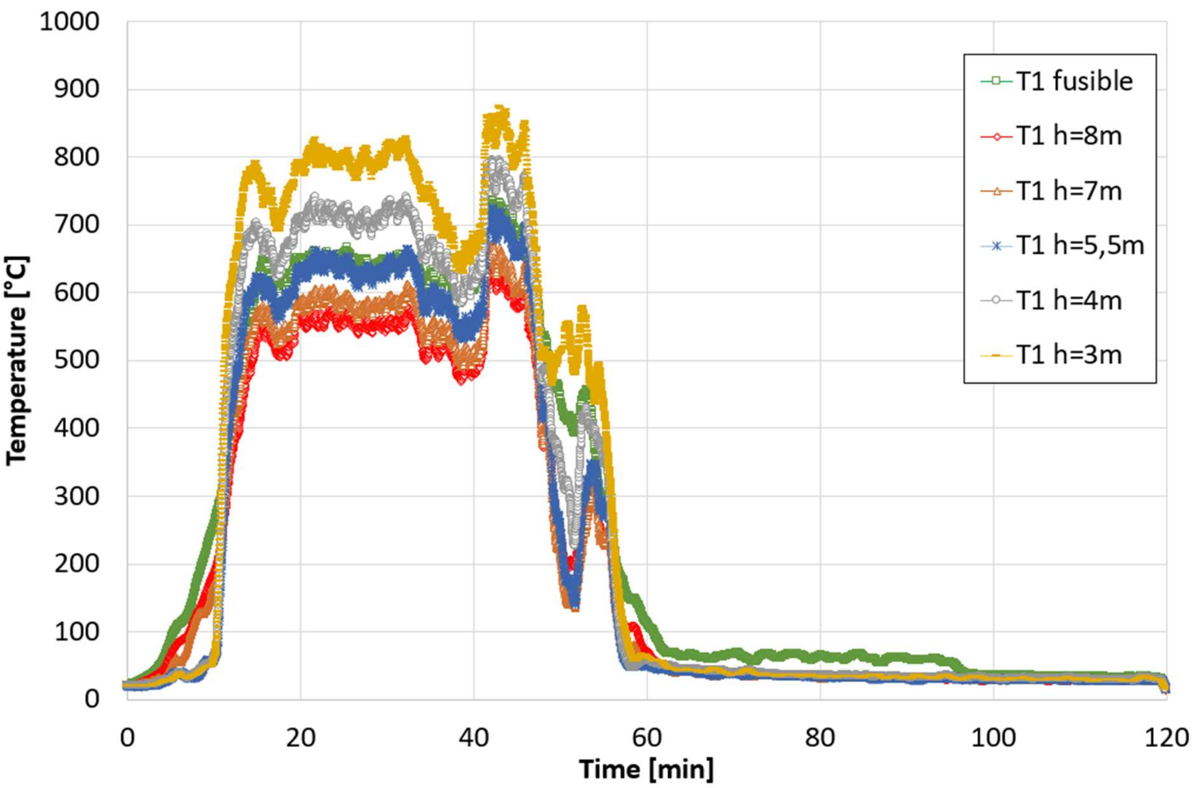
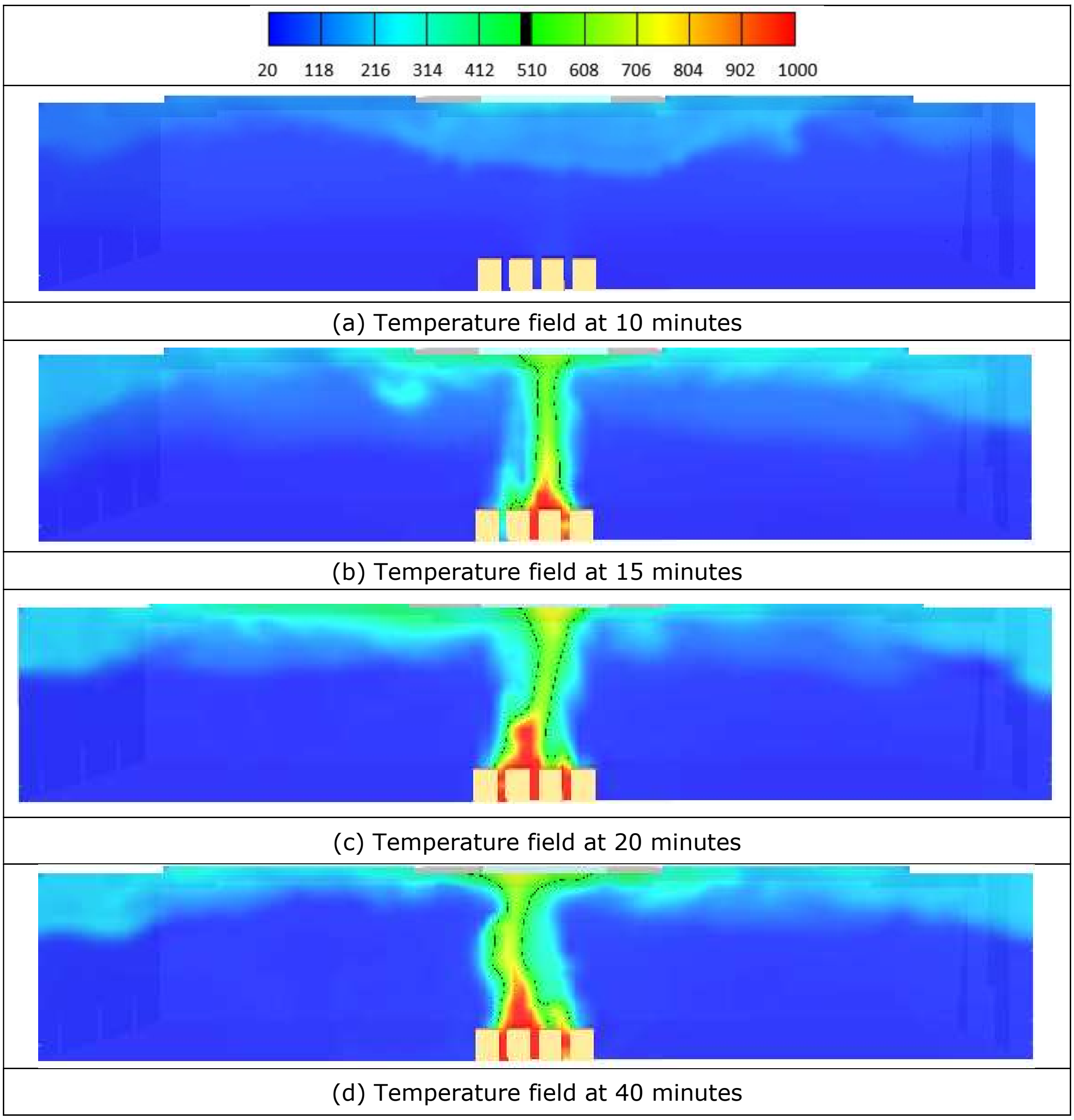


Figure 144: Gas temperatures vs time along the wall height at the location of thermocouple T1



(a) Temperature field at 10 minutes

(b) Temperature field at 15 minutes

(c) Temperature field at 20 minutes

(d) Temperature field at 40 minutes

Figure 145: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.15. Scenario I.2.3

In this case, the building has a floor area of about 3 100 m², and a bulk storage is considered. This storage is located in the centre of the building. This scenario concerns a 3100m² industrial building with a bulk storage, located in the middle of the building.

The calculated HRR is shown in Figure 146. The maximum HRR is about 27 MW. The plan views in Figure 147 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. Considering the large volume of the building, this fire can be considered as a "localized fire". The bulk storage is fully involved in fire at 20 minutes.

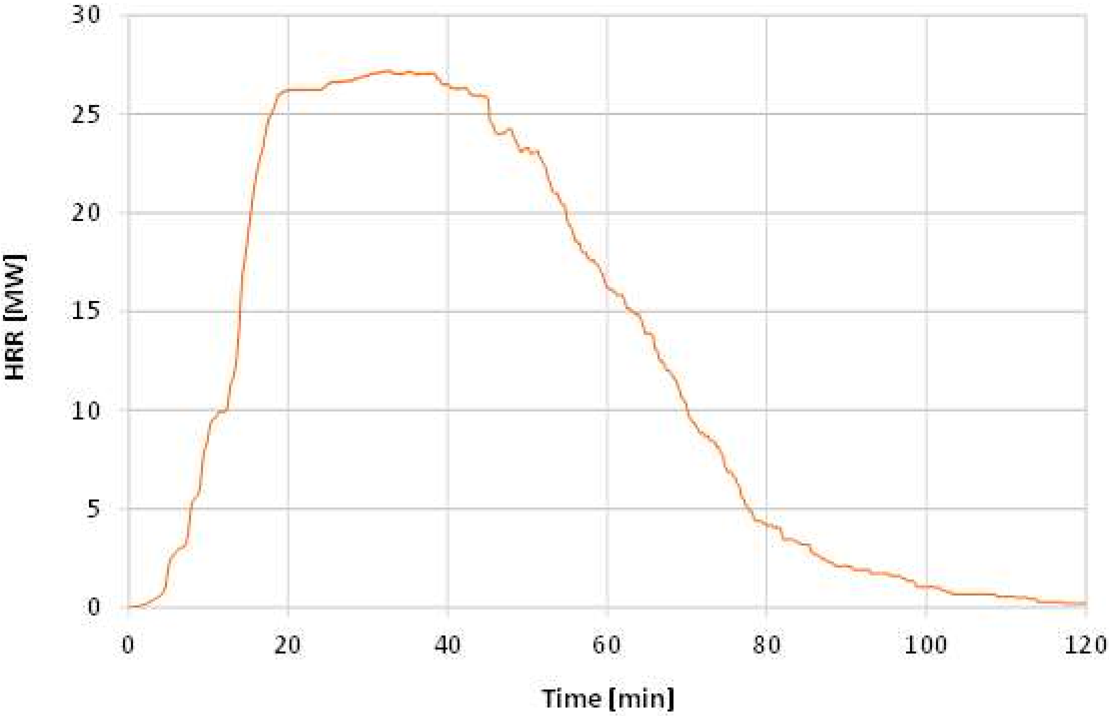
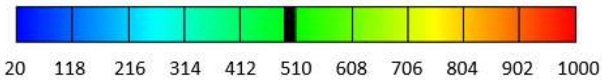
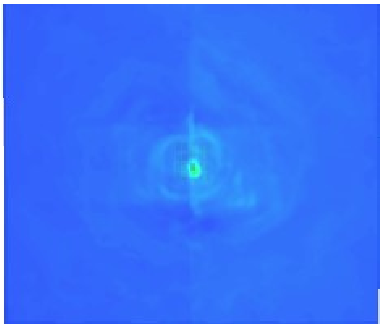
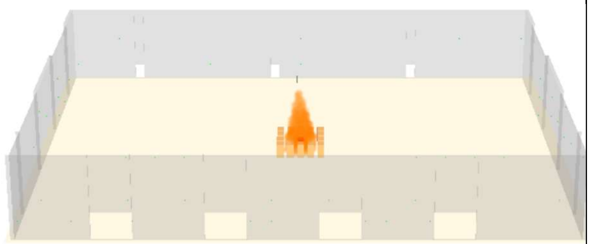
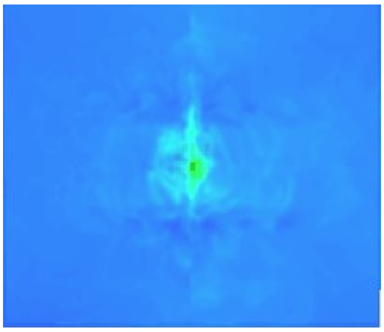
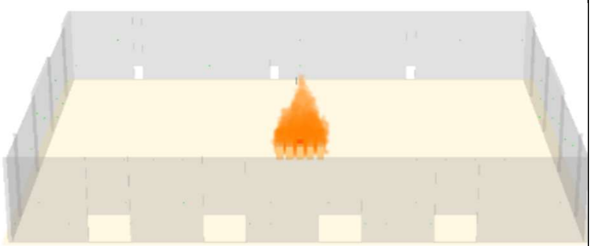


Figure 146: HRR calculated for the scenario I.2.3



	
(a) Plan view 1m under the roof at 10 minutes	(b) Pallets involved in fire at 10 minutes
	
(c) Plan view 1m under the roof at 15 minutes	(d) Pallets involved in fire at 15 minutes

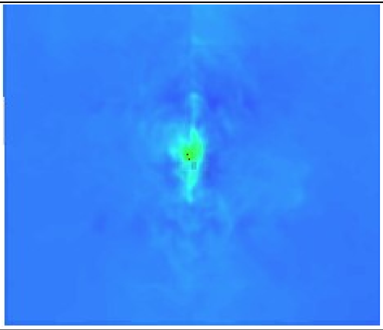
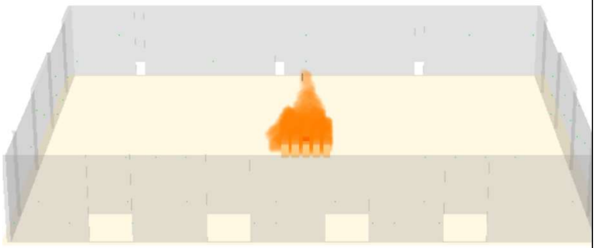
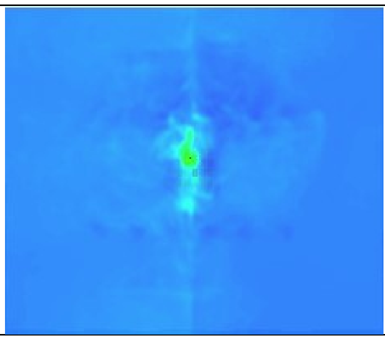
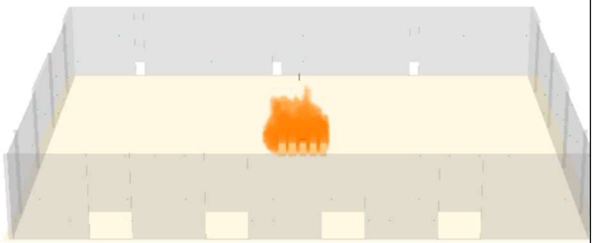
	
(e) Plan view 1m under the roof at 20 minutes	(f) Pallets involved in fire at 20 minutes
	
(g) Plan view 1m under the roof at 40 minutes	(h) Pallets involved in fire at 40 minutes

Figure 147: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 148 shows the gas temperatures calculated at 1m under the roof directly above the ignition position and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), close or far away from the fire source (as indicated in Figure 149). Excepted directly above the fire, maximum temperatures in the hot gas layer are about 150°C.

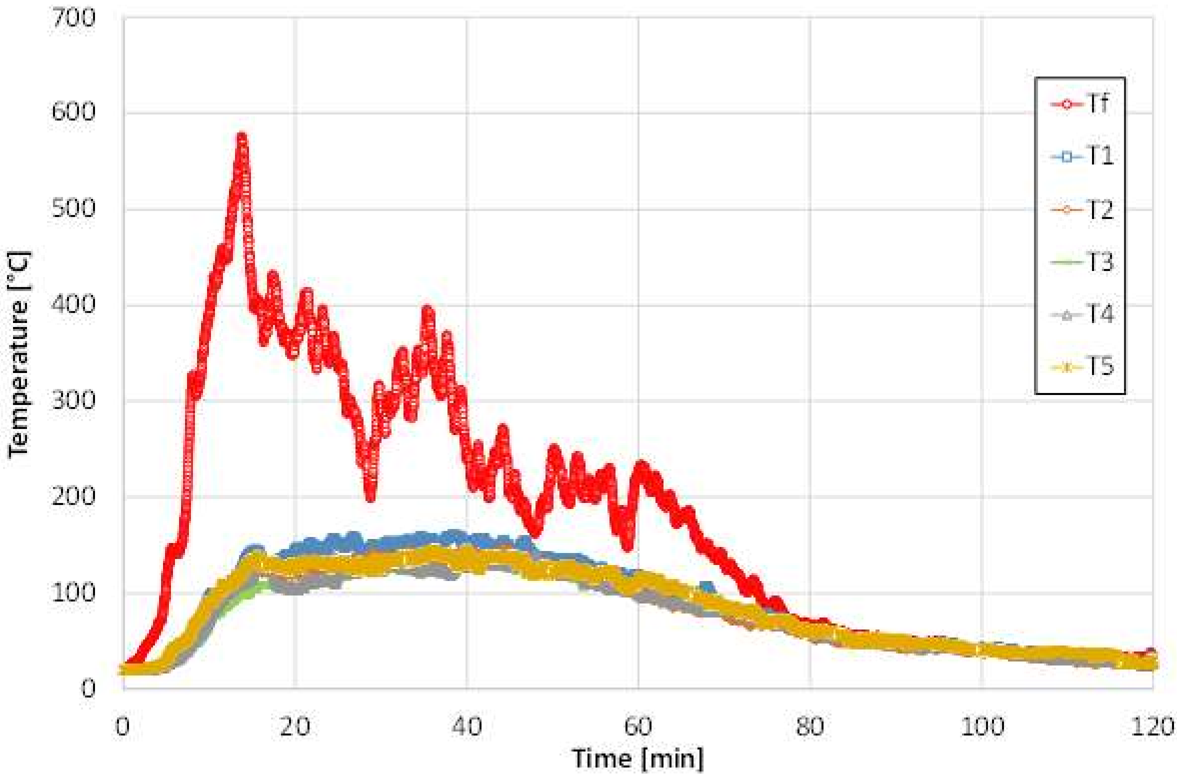


Figure 148: Gas temperature at different locations under the roof

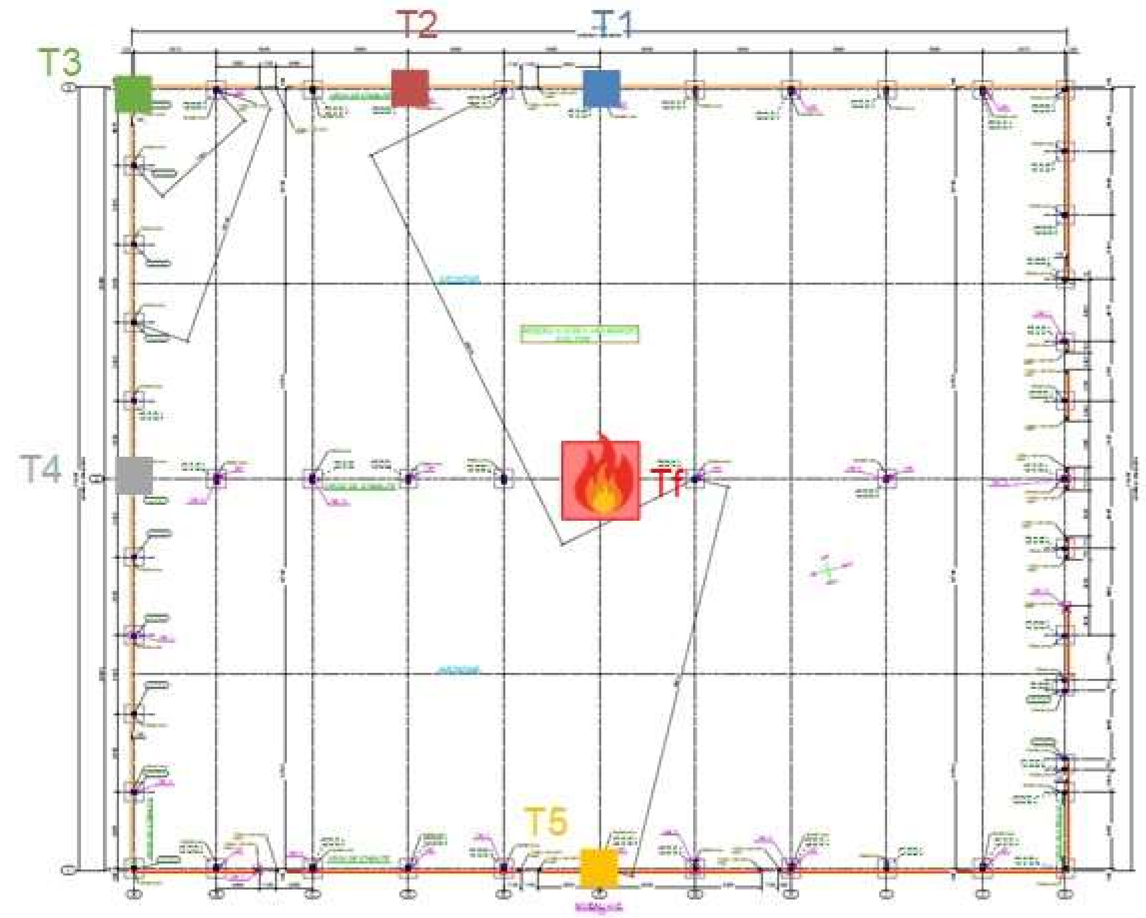


Figure 149: Temperature measurement point Locations

Gas temperatures calculated at different wall heights nearest the fire source, at the same location as thermocouple T1, are shown in Figure 150. Only the upper parts are subjected to the hot gas layer.

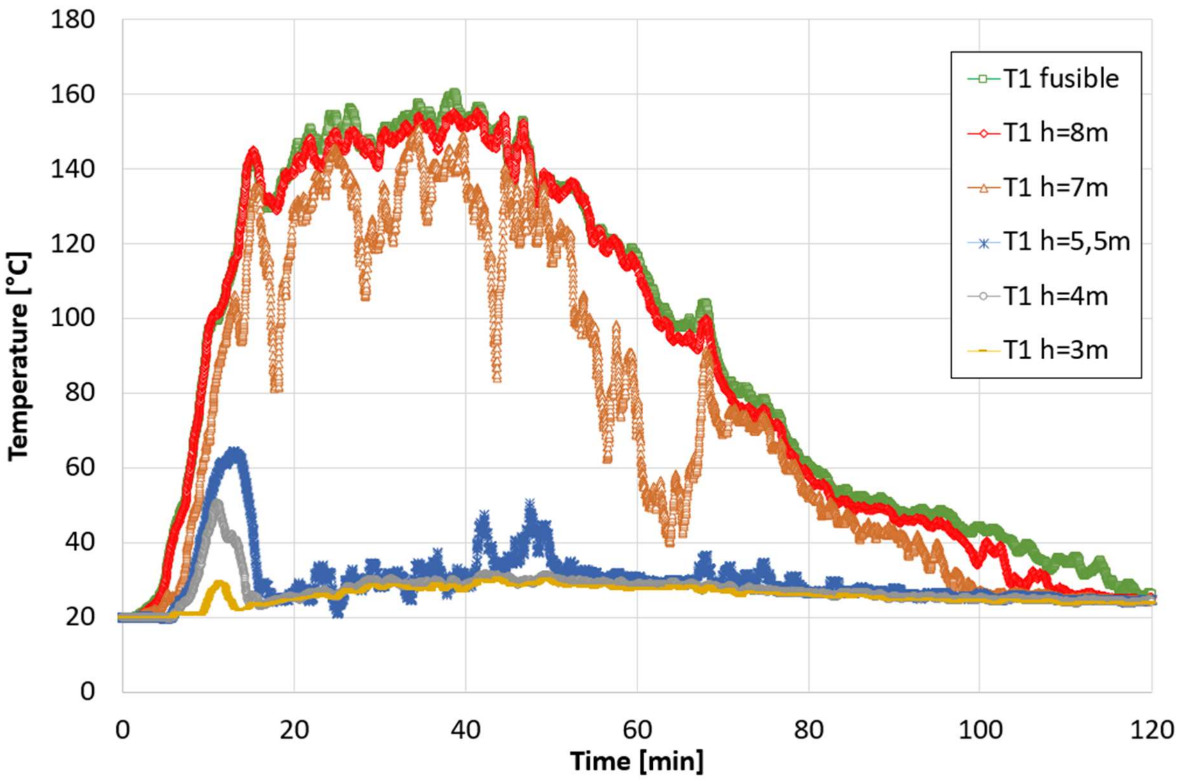
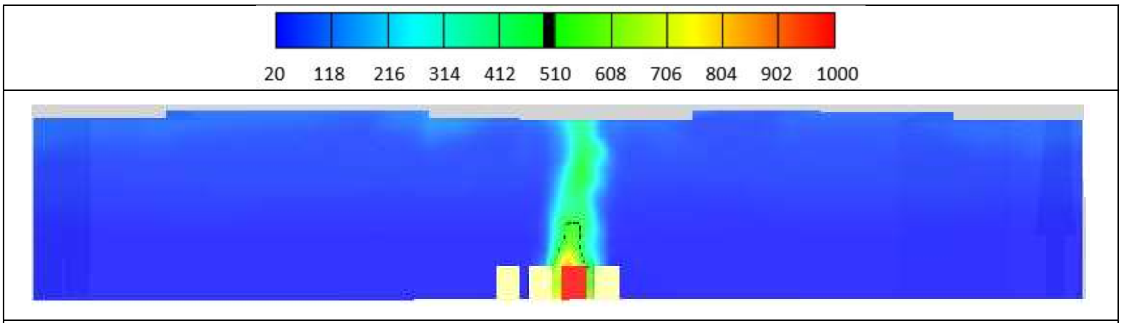
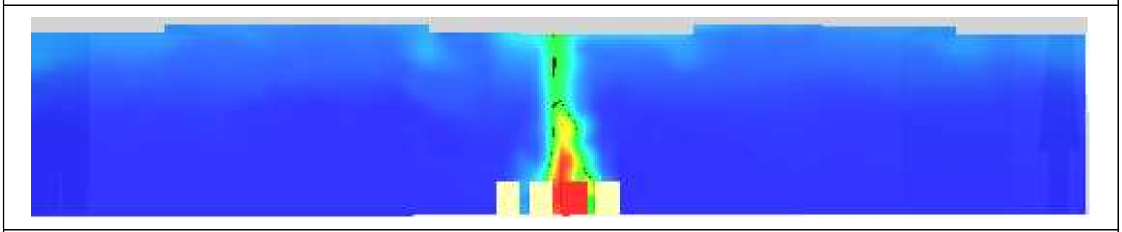


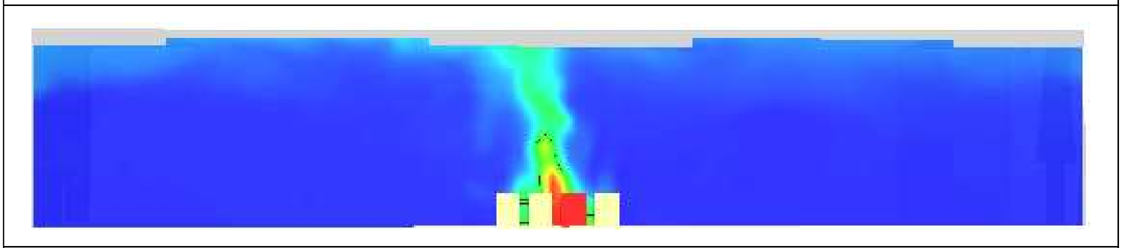
Figure 150: Gas temperatures vs time along the wall height at the location of thermocouple T1



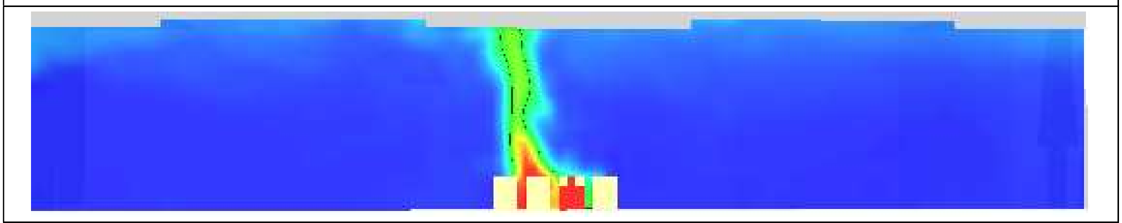
(a) Temperature field at 10 minutes



(b) Temperature field at 15 minutes



(c) Temperature field at 20 minutes



(d) Temperature field at 40 minutes

Figure 151: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.16. Scenario W.3.1

This scenario concerns a 6000m² warehouse with a racking storage system. The source of fire is situated in the middle of a single row rack near one of the longer building walls

The calculated HRR is shown in Figure 152. The plan views in Figure 153 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. A flashover occurs between 25 and 34 minutes due to the quick fire propagation at the upper part of the rack storage. Although the opening area is important (9% of the roof surface), the natural smoke extraction flow is not enough to efficiently evacuate the heat generated by the fire. After 75 minutes, the amount of fuels gradually decreases with the combustion until the total extinction of the fire due to a lack of combustible.

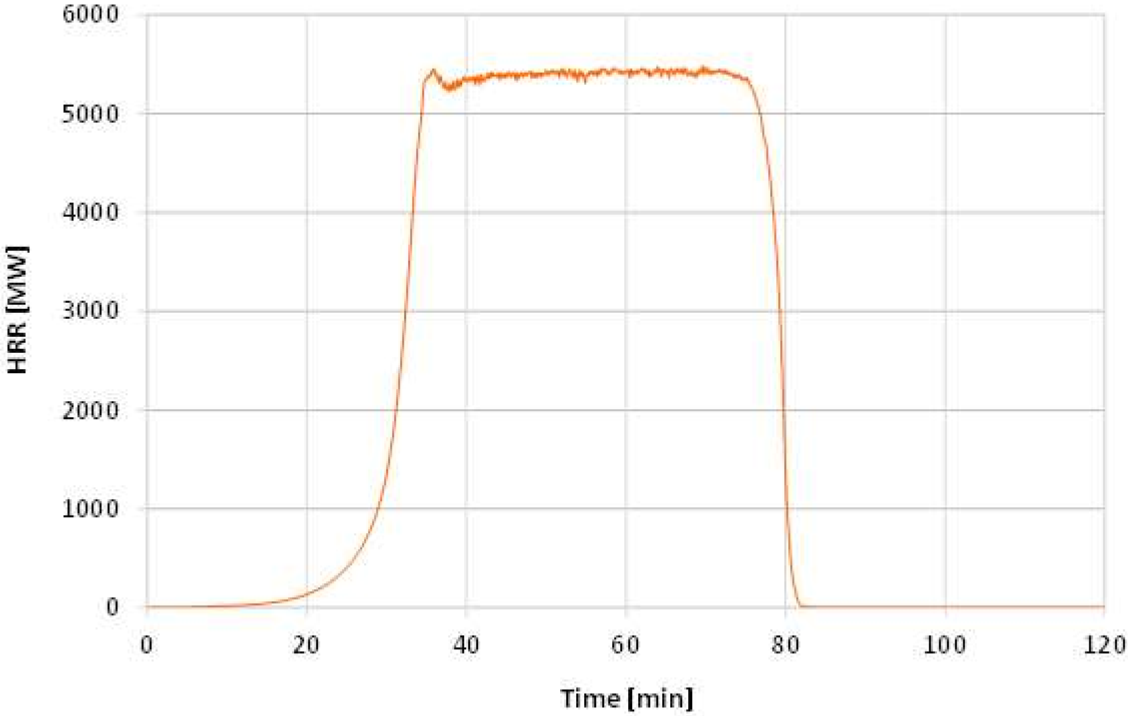
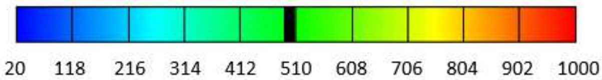
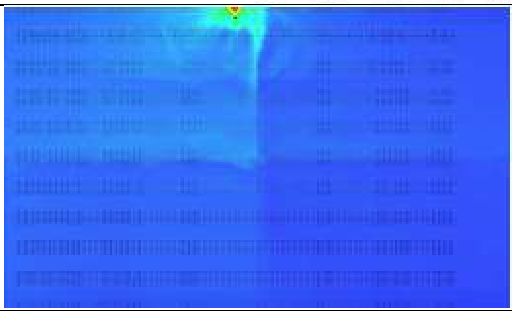
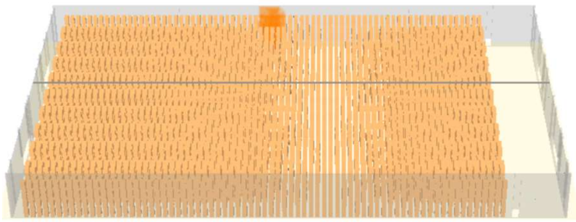
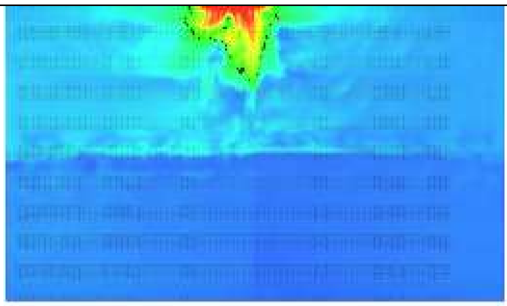
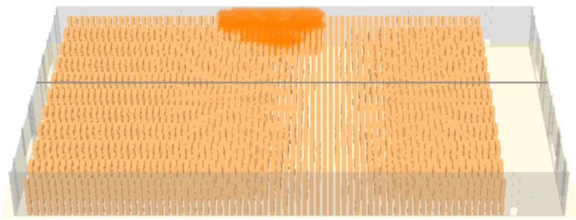
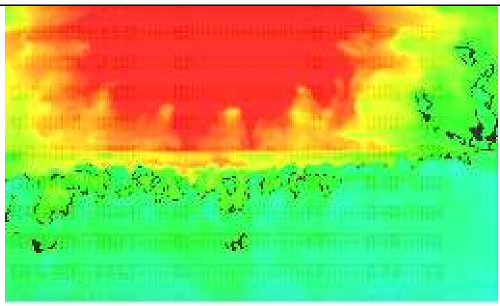
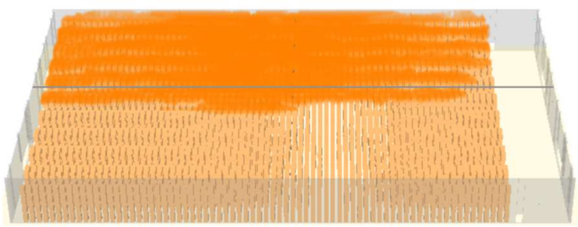
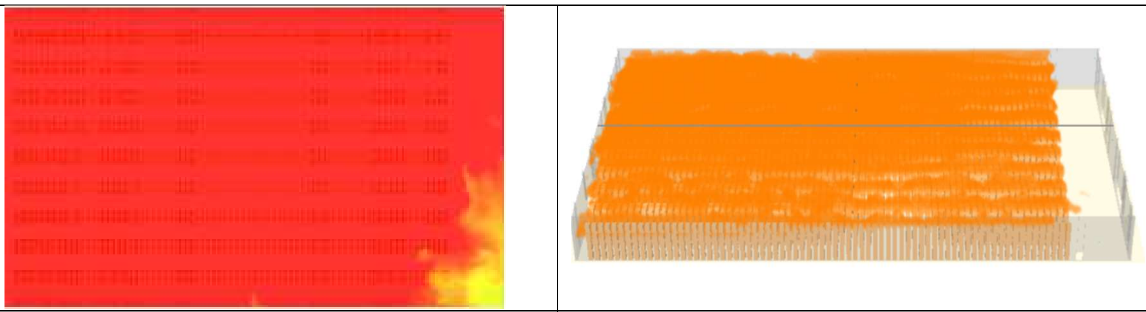


Figure 152: HRR calculated for the scenario W.3.1



	
(a) Plan view 1m under the roof at 10 minutes	(b) Pallets involved in fire at 10 minutes
	
(c) Plan view 1m under the roof at 20 minutes	(d) Pallets involved in fire at 20 minutes
	
(e) Plan view 1m under the roof at 30 minutes	(f) Pallets involved in fire at 30 minutes



(g) Plan view 1m under the roof at 34 minutes	(h) Pallets involved in fire at 34 minutes

Figure 153: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 153 shows the gas temperatures calculated at 1m under the roof directly above location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 154). Gas temperatures reach 1000°C at 8 minutes directly above the ignition position and at thermocouple T1. At 34 minutes, 1000°C gas temperature is obtained for the whole surface of the warehouse at 10 m height (Figure 153g).

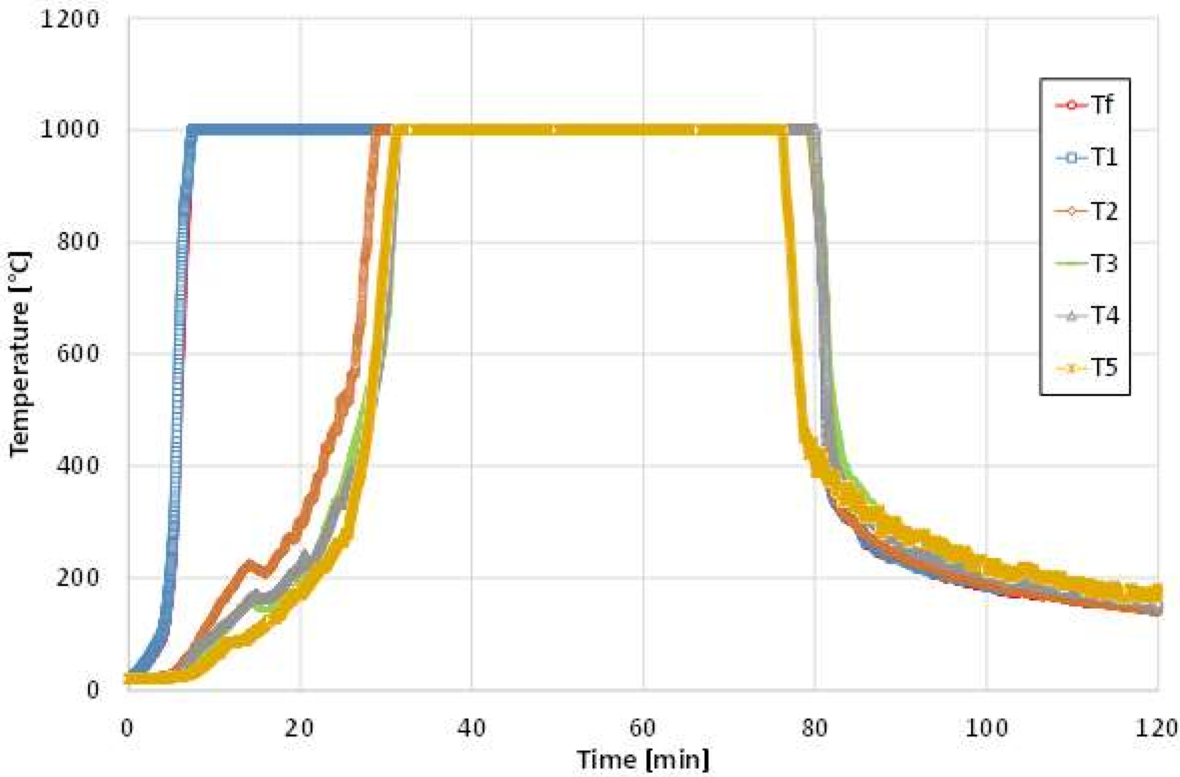


Figure 154: Gas temperature at different locations under the roof

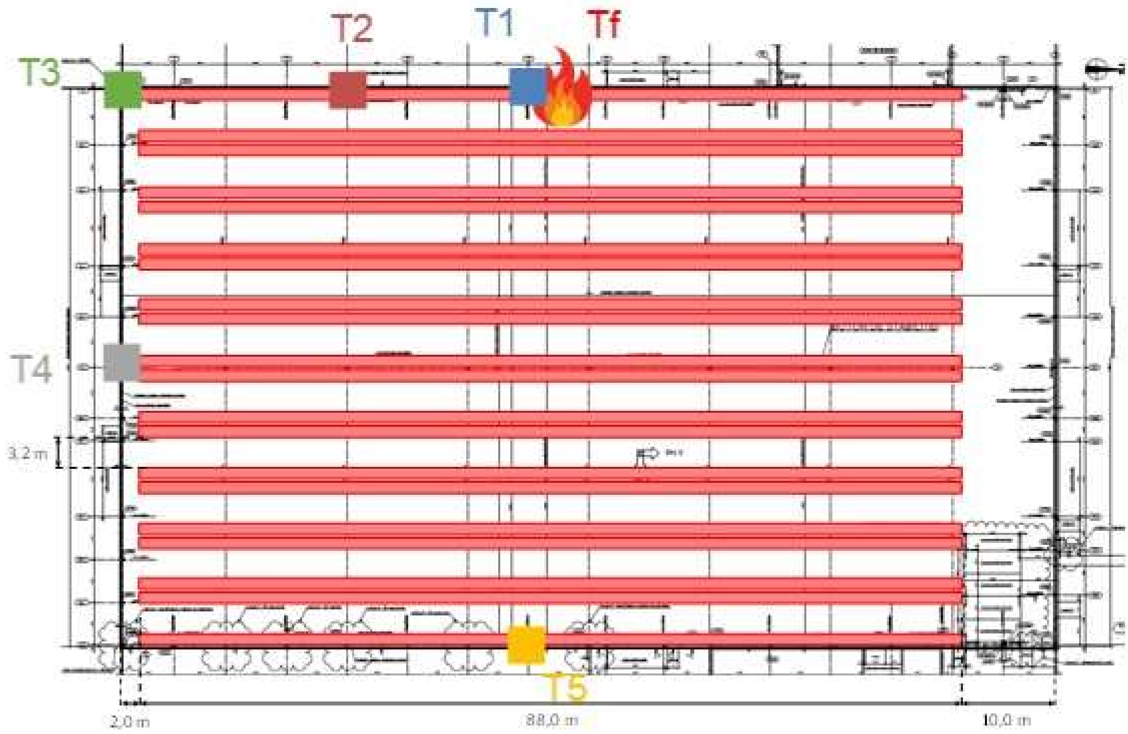


Figure 155: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple T1, are shown in Figure 156. It can be noted that hot gases are uniformely distributed along the wall height at this location

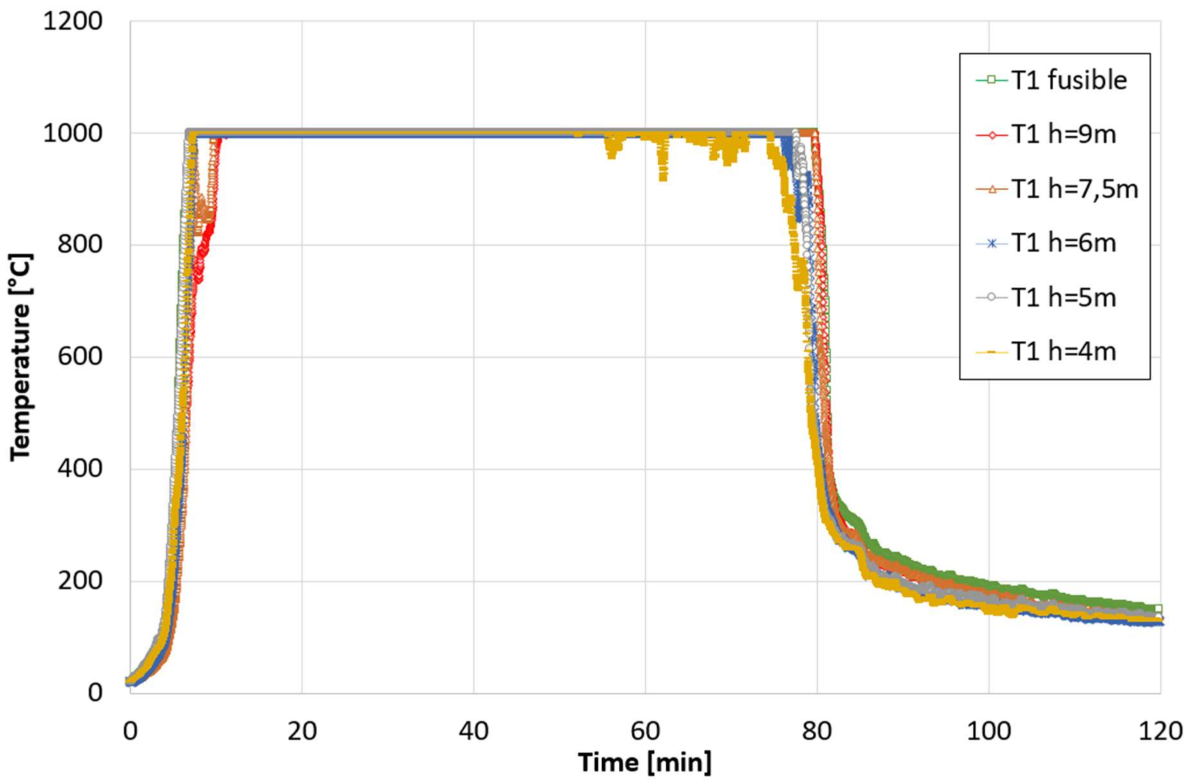
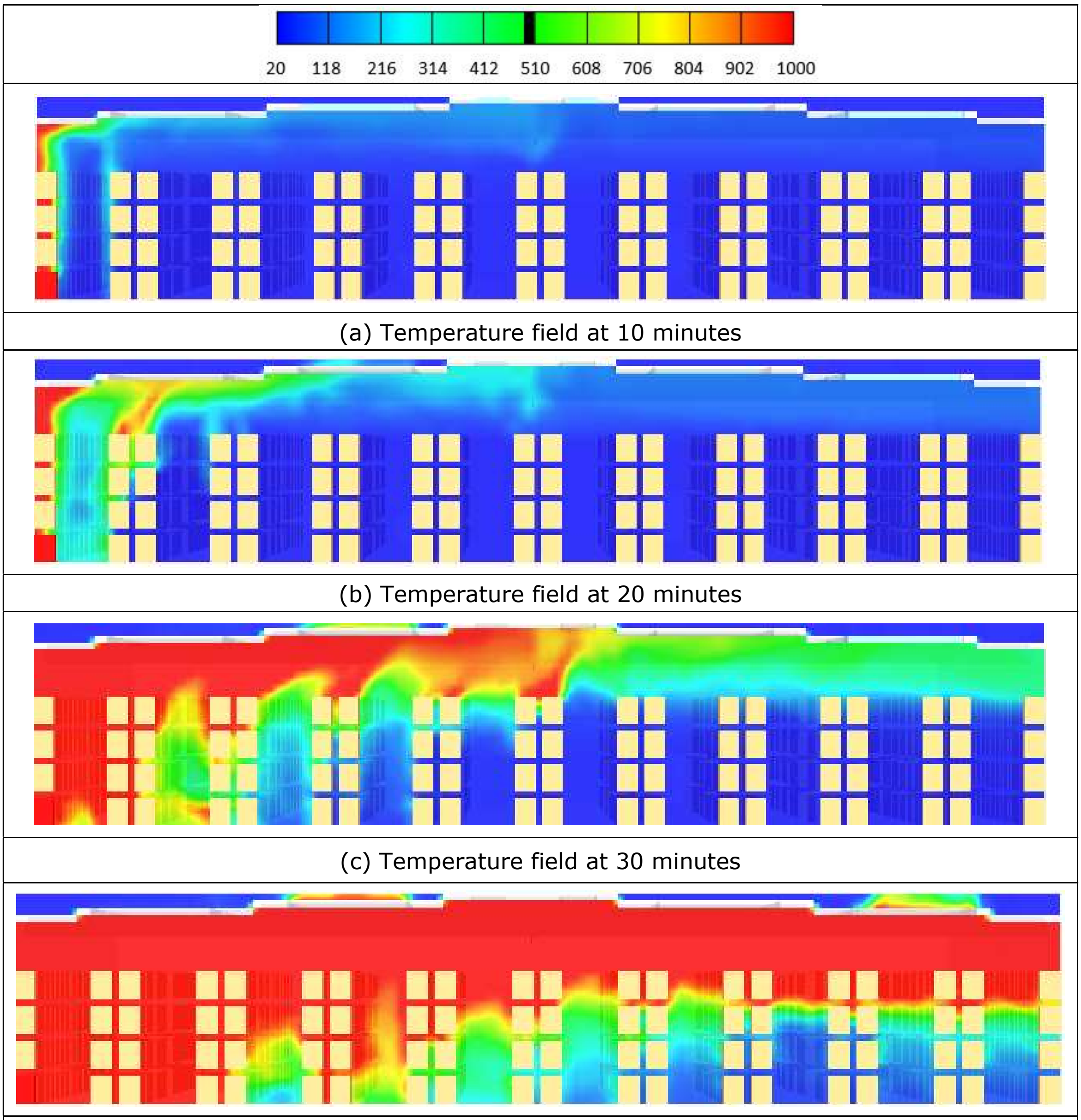


Figure 156: Gas temperatures vs time along the wall height at the location of thermocouple T1



(a) Temperature field at 10 minutes

(b) Temperature field at 20 minutes

(c) Temperature field at 30 minutes

(d) Temperature field at 34 minutes

Figure 157: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.17. Scenario W.3.2

This scenario concerns a 600m² warehouse with a racking storage system. The source of fire is situated at the end of the central double row racks, near one of the shorter building walls.

The calculated HRR is shown in Figure 158. The plan views in Figure 159 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. A flashover occurs between 35 and 42 minutes (Figure 159), due to the quick fire propagation at the upper part of the rack storage. Although the opening area is important (9% of the roof surface), the natural smoke extraction flow is not enough to effectively evacuate the heat generated by the fire.

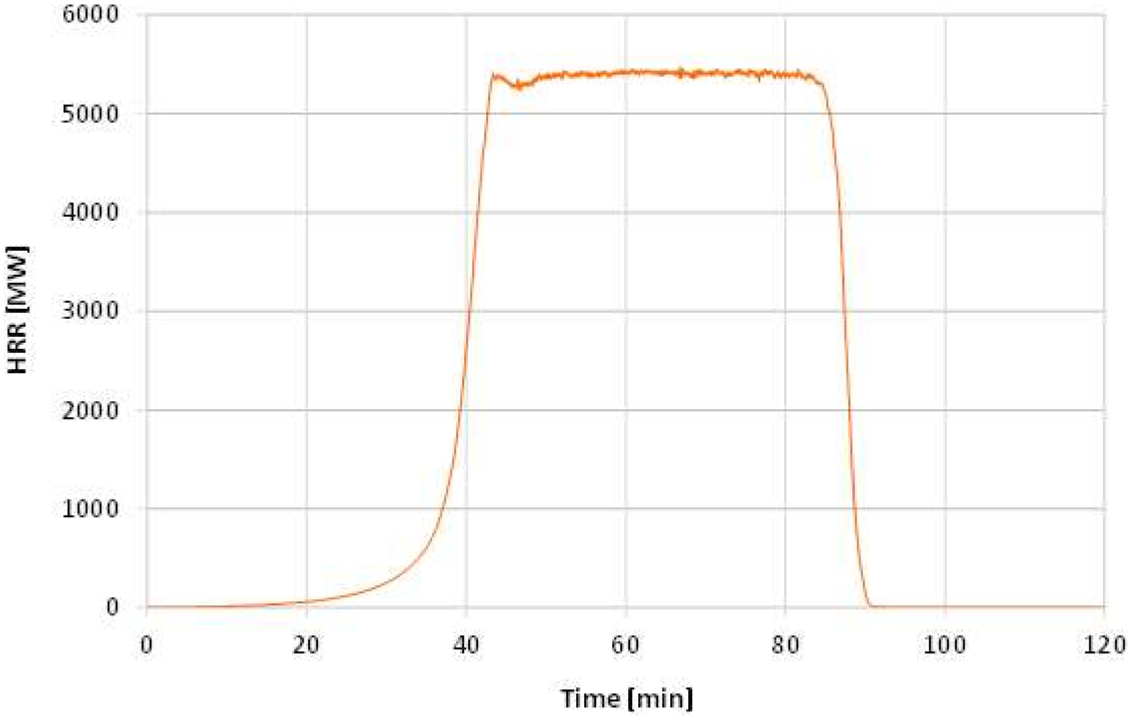
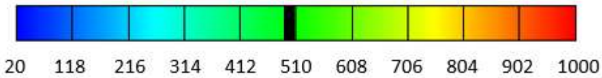
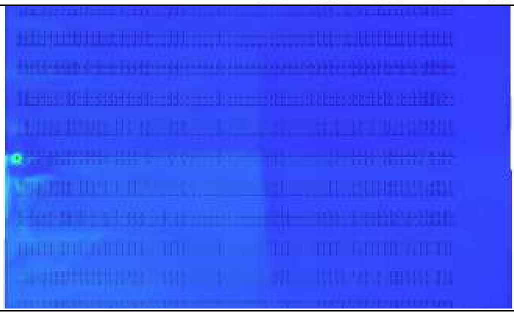
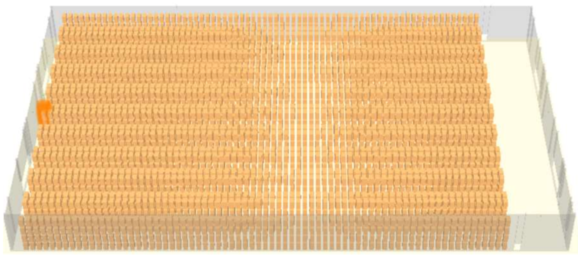
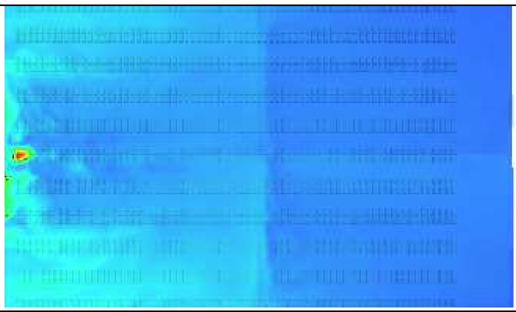
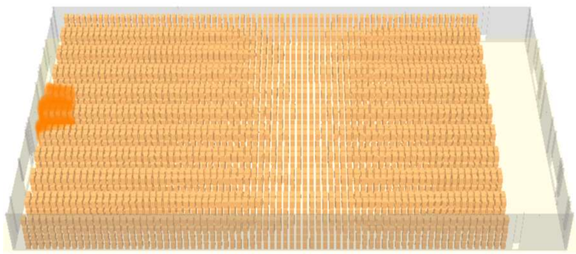
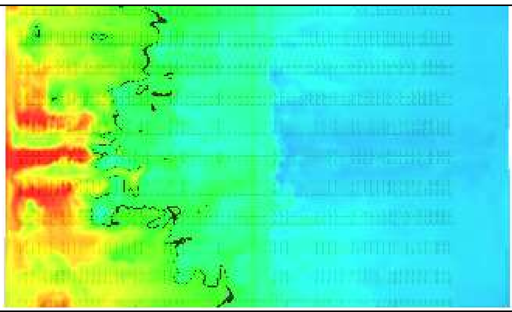
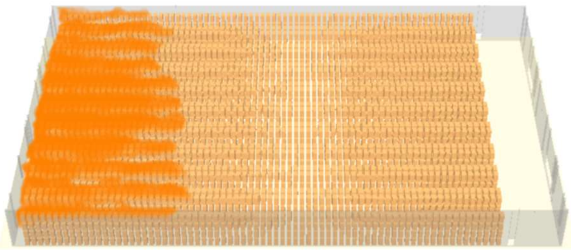
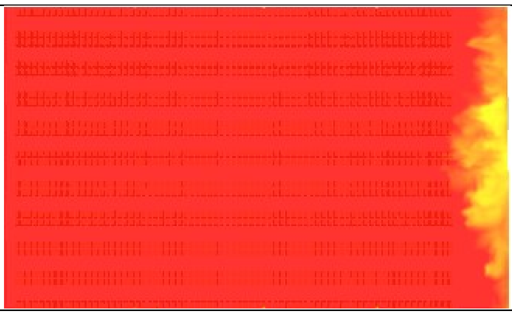


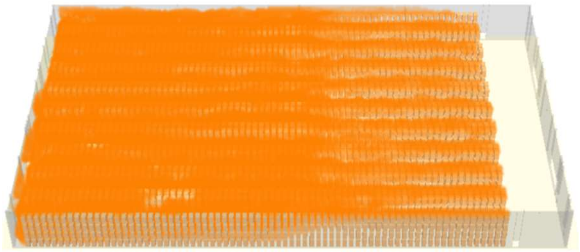
Figure 158: HRR calculated for the scenario W.3.2



	
(a) Plan view 1m under the roof at 10 minutes	(b) Pallets involved in fire at 10 minutes
	
(c) Plan view 1m under the roof at 20 minutes	(d) Pallets involved in fire at 20 minutes
	
(e) Plan view 1m under the roof at 35 minutes	(f) Pallets involved in fire at 35 minutes



(g) Plan view 1m under the roof at 42 minutes



(h) Pallets involved in fire at 42 minutes

Figure 159: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 160 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 161). Gas temperatures reach 1000°C at 20 minutes above the ignition position and at 33 minutes at thermocouple T1. At 42 minutes, 1000°C gas temperature is obtained for the whole surface of the building at 10 m height (Figure 159g). It should be noted that the initial fire propagation is slower than the previous case (scenario W.3.1), because the fire starts at the end of a rack.

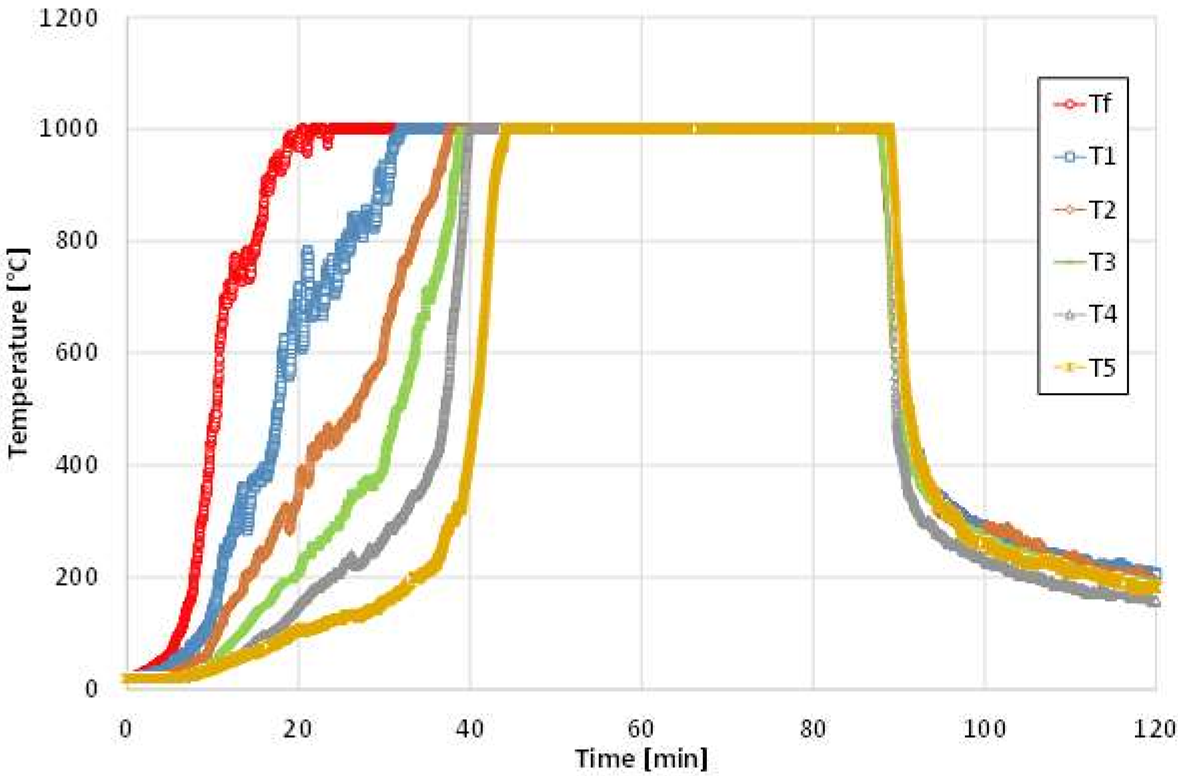


Figure 160: Gas temperature at different locations under the roof

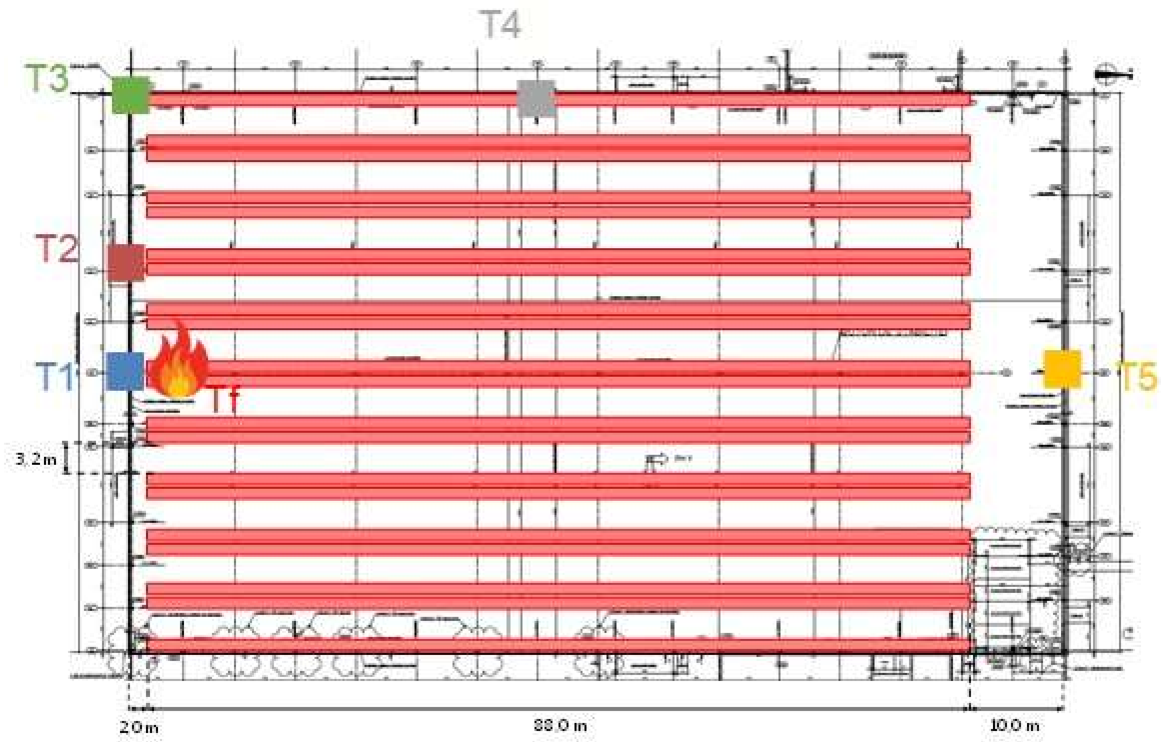


Figure 161: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple T1, are shown in Figure 162. The gas temperature increases more slowly at the lower parts. However, high gas temperatures are observed in almost all the volume of the building after 42 minutes.

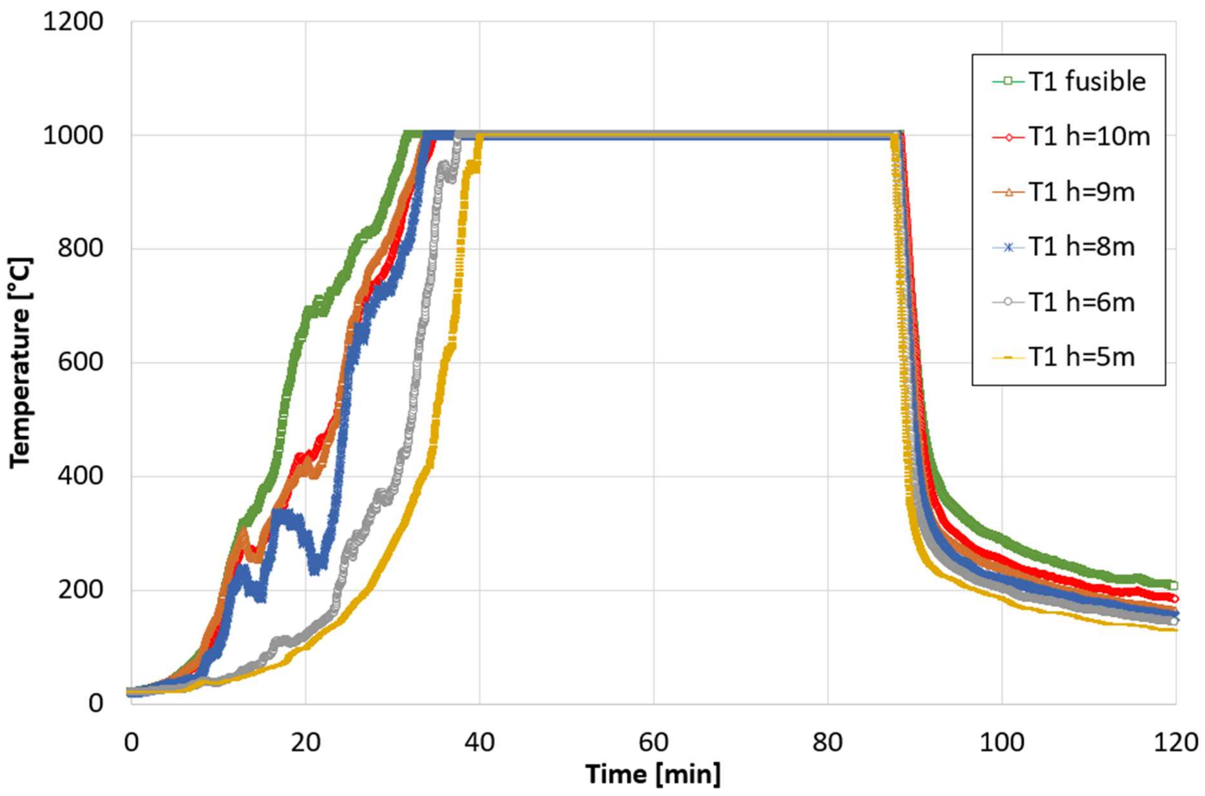
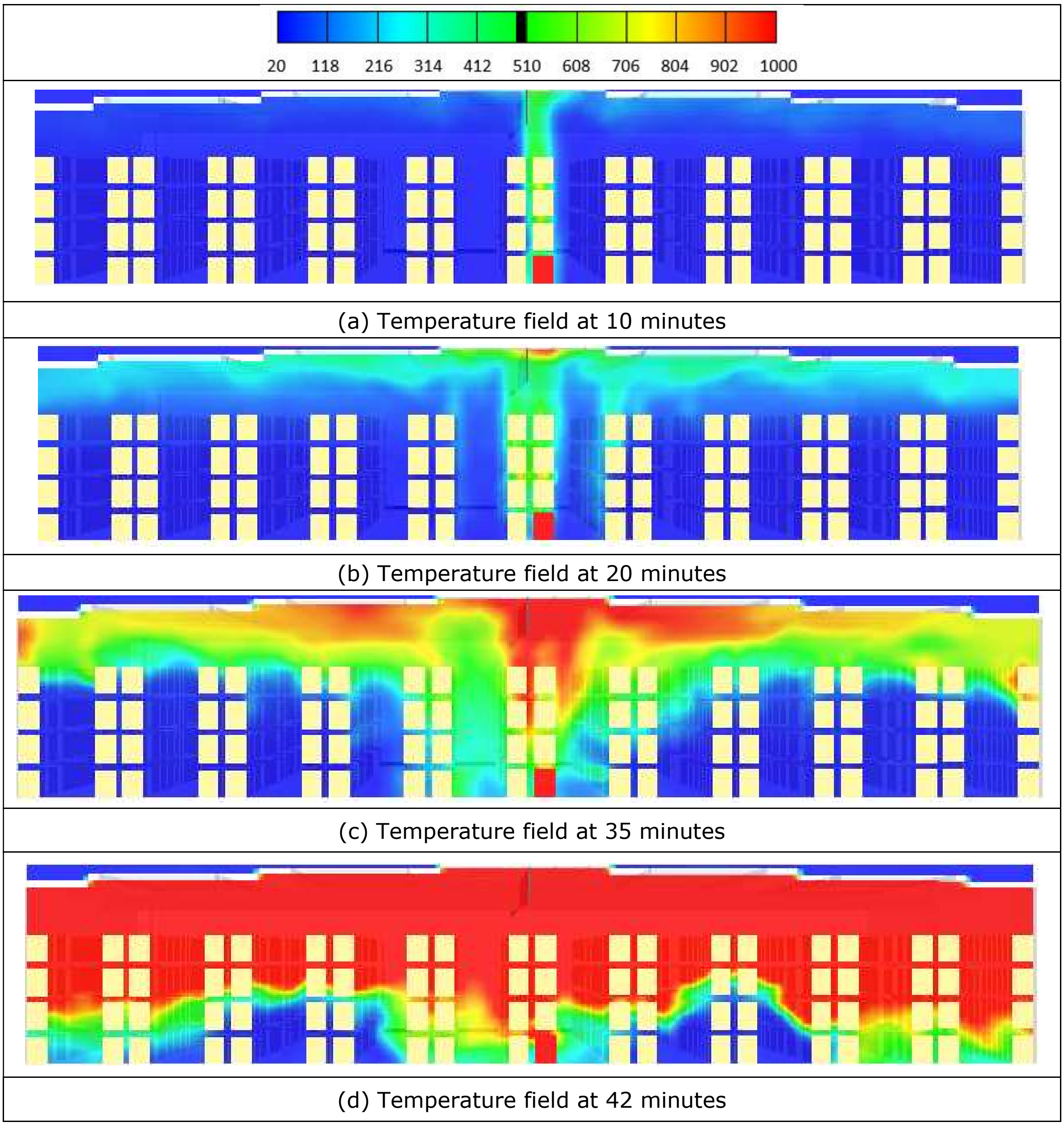


Figure 162: Gas temperatures vs time along the wall height at the location of thermocouple T1



(a) Temperature field at 10 minutes

(b) Temperature field at 20 minutes

(c) Temperature field at 35 minutes

(d) Temperature field at 42 minutes

Figure 163: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.18. Scenario W.3.3

This scenario concerns a 6000m² warehouse with a racking storage system. The source of fire is situated in the middle of a central double row rack.

The calculated HRR is shown in Figure 164. The plan views in Figure 165 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. A flashover occurs between 29 and 34 minutes (Figure 165), due to the quick fire propagation at the upper part of the rack storage. Although the opening area is important (9% of the roof surface), the natural smoke extraction flow is not enough to effectively evacuate the heat generated by the fire.

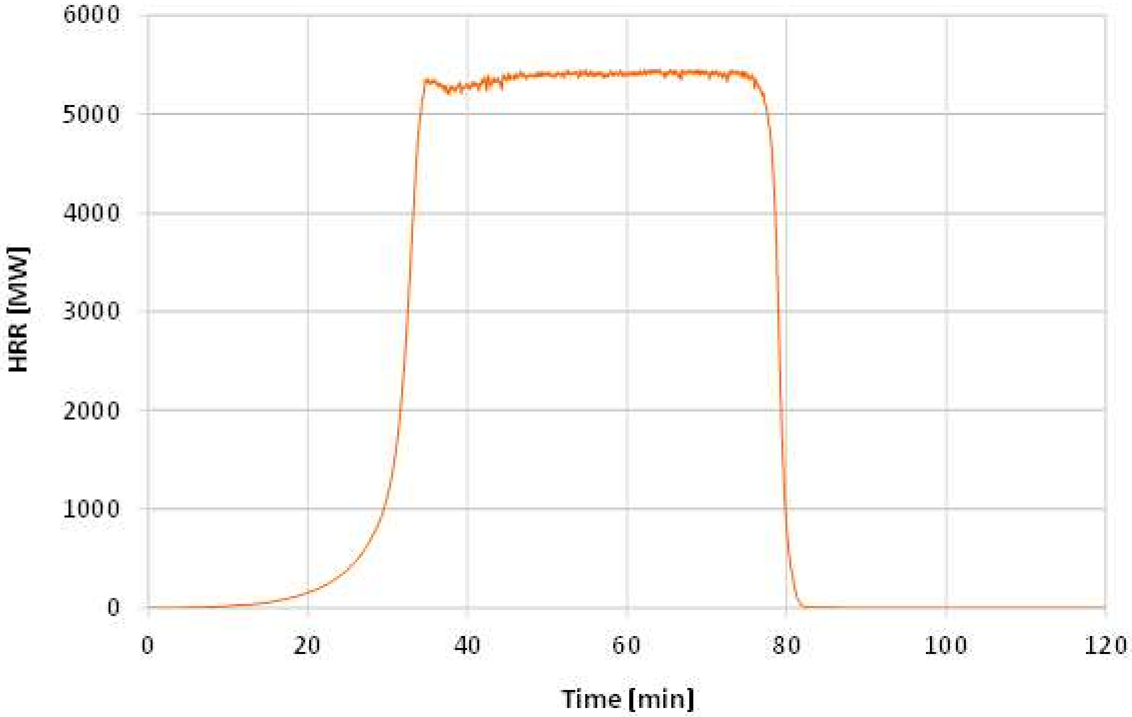
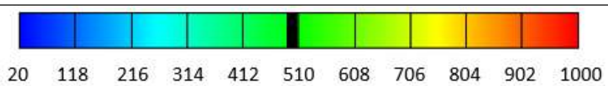
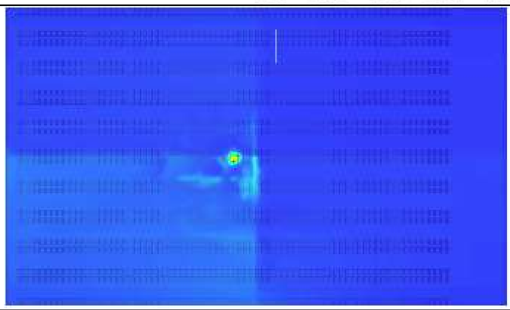
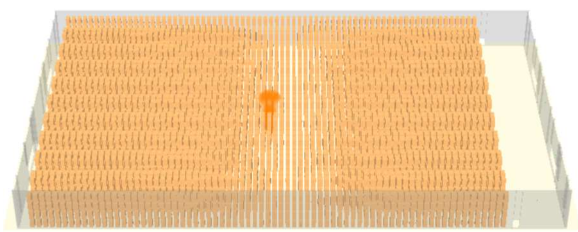


Figure 164: HRR calculated for the scenario W.3.2

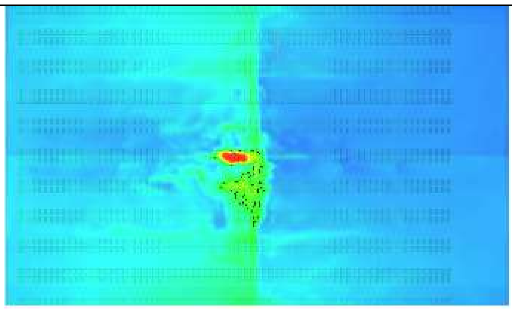




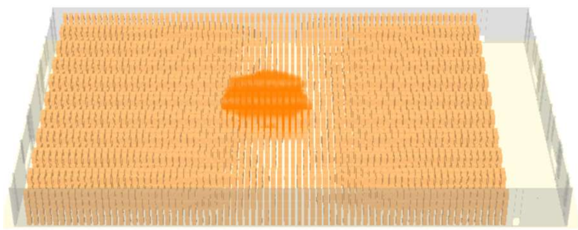
(a) Plan view 1m under the roof at 10 minutes



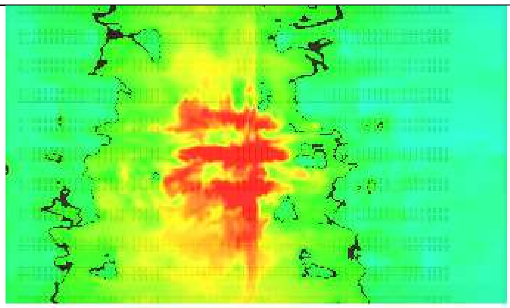
(b) Pallets involved in fire at 10 minutes

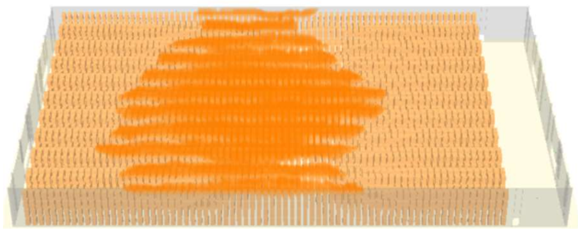


(c) Plan view 1m under the roof at 20 minutes



(d) Pallets involved in fire at 20 minutes





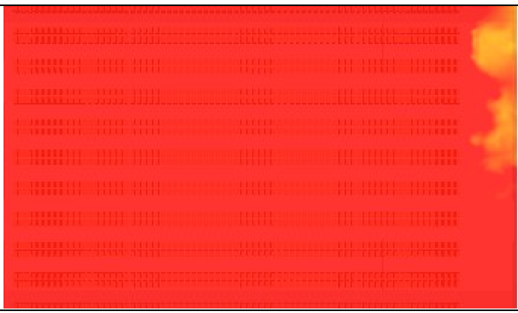
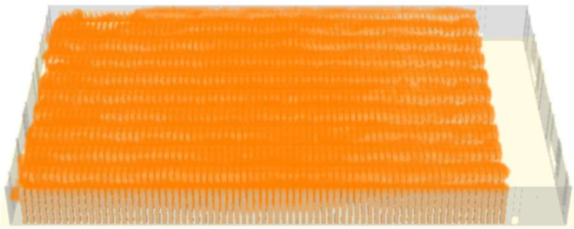
(e) Plan view 1m under the roof at 29 minutes	(f) Pallets involved in fire at 29 minutes
	
(g) Plan view 1m under the roof at 34 minutes	(h) Pallets involved in fire at 34 minutes

Figure 165: Temperature fields (°C) under the roof and surfaces involved in the fire

Figure 166 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 167). Gas temperatures reach 1000°C at 11 minutes directly above the ignition position (thermocouple Tf). At 34 minutes, 1000°C gas temperature is obtained for the whole surface of the building at 10 m height (Figure 165g).

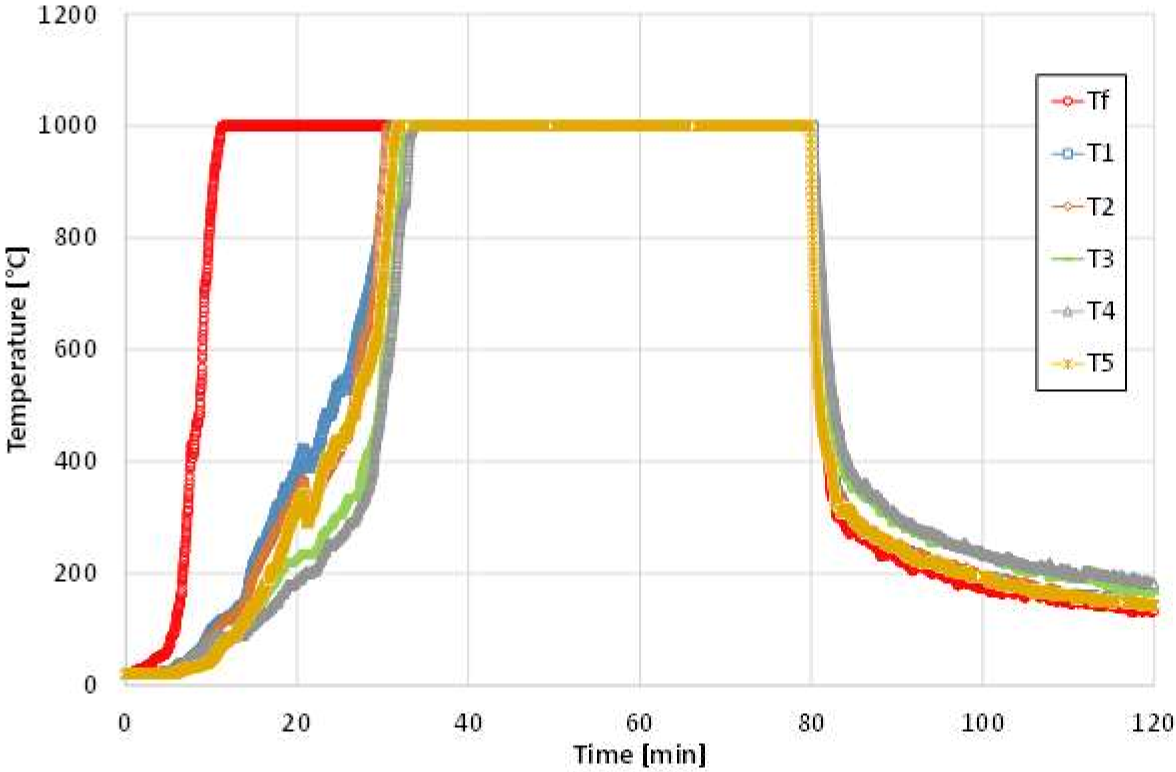


Figure 166: Gas temperature at different locations under the roof

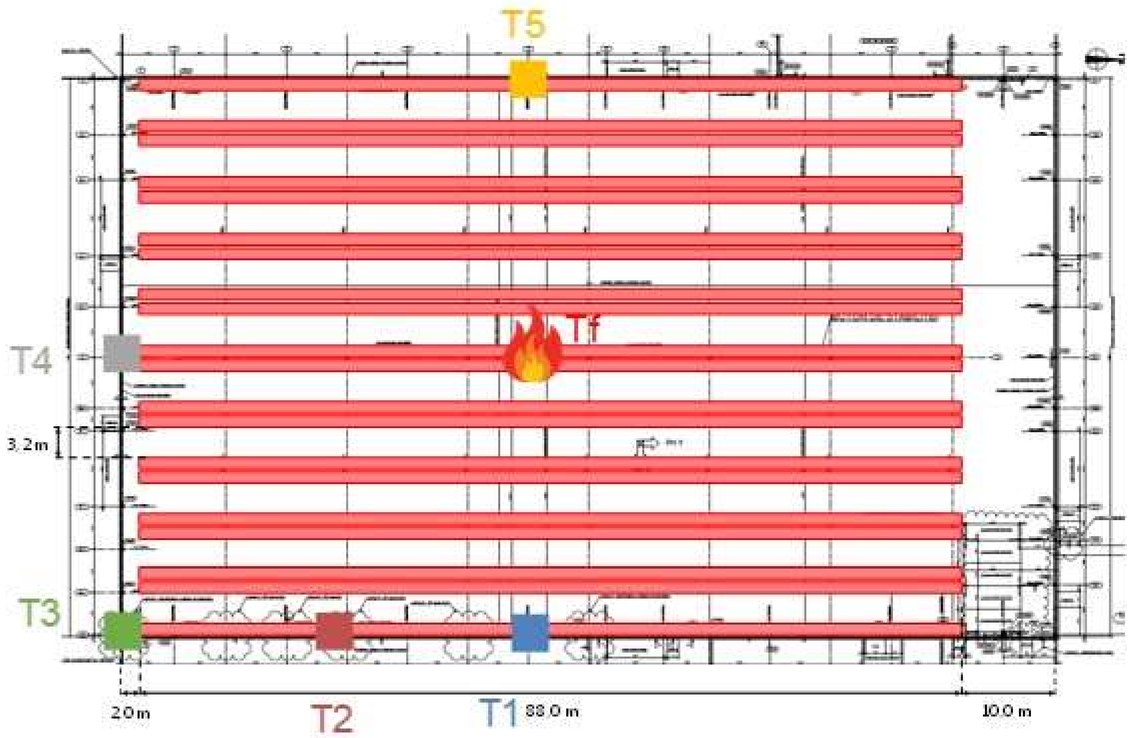


Figure 167: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple T1, are shown in Figure 168. The gas temperature increases more slowly at the lower parts. However, high gas temperatures are observed in almost all the volume of the warehouse after 34 minutes.

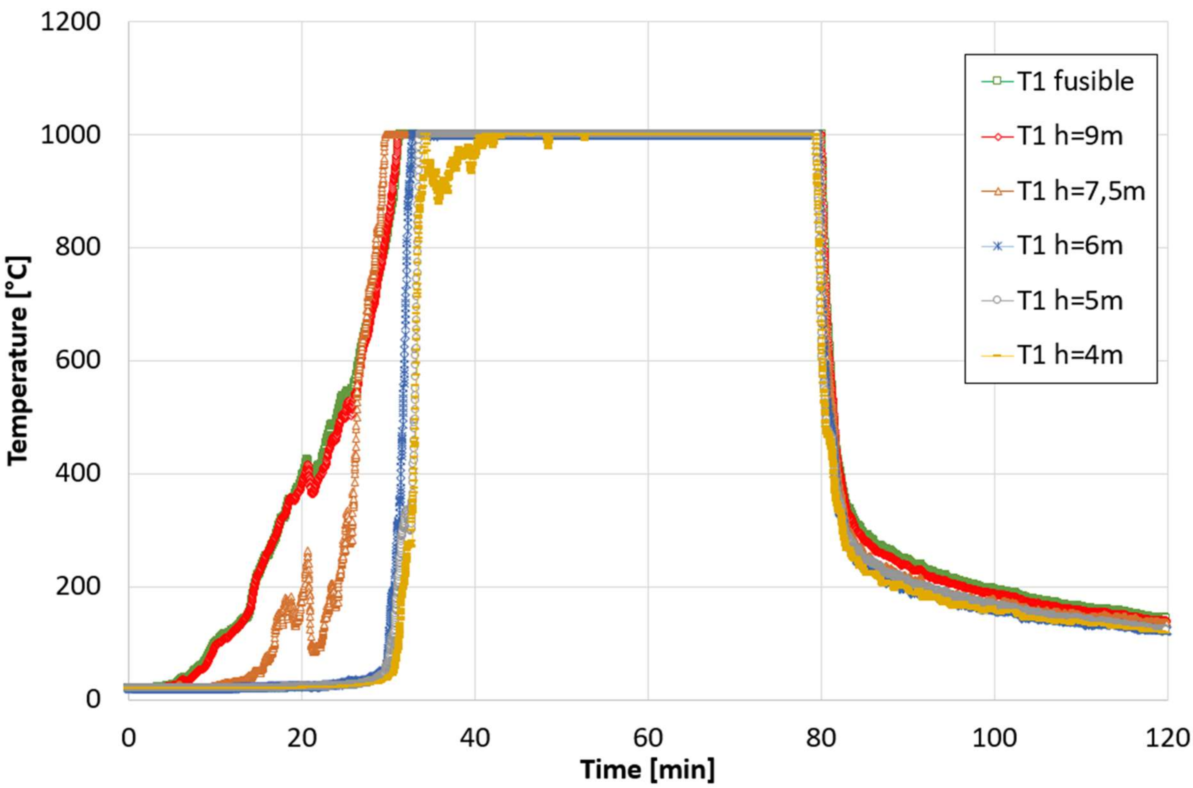
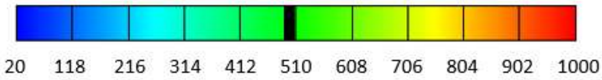
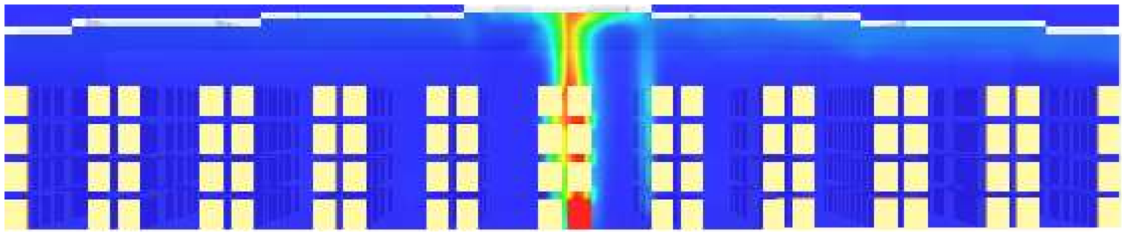
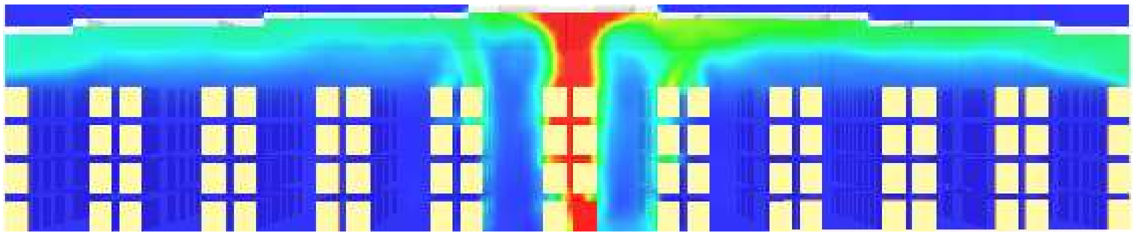


Figure 168: Gas temperatures vs time along the wall height at the location of thermocouple T1

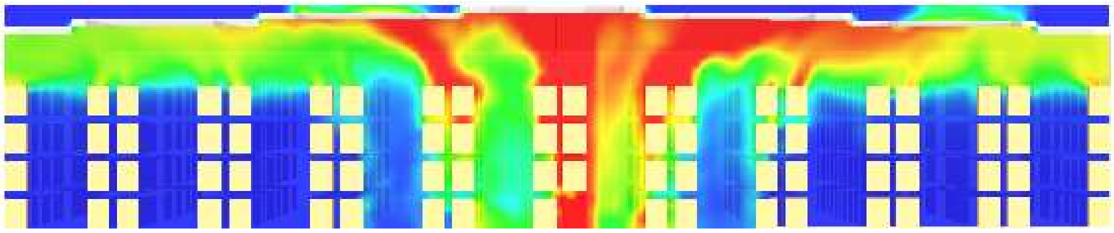




(a) Temperature field at 10 minutes



(b) Temperature field at 20 minutes



(c) Temperature field at 29 minutes

(d) Temperature field at 34 minutes

Figure 169: Temperature fields (°C) in the plan of the steel portal frame the nearest of the fire source

A.19. Scenario W.4.1

This scenario concerns a 12000m² warehouse with a racking storage system. The source of fire is situated in the middle of a single row rack placed along one of the longer building walls.

The calculated HRR is shown Figure 170. The plan views in Figure 171 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. The volume of the warehouse and its height delay the flashover until 73 minutes with the burning of the rack at the opposite side of the building (Figure 171h). However, pallets involved in the ignition started to burn out at this moment. After 82 minutes, a large part of the pallets of the warehouse is still not burning (Figure 171j). Although, gas temperature under the roof reaches 1000°C in all the left zone of the building.

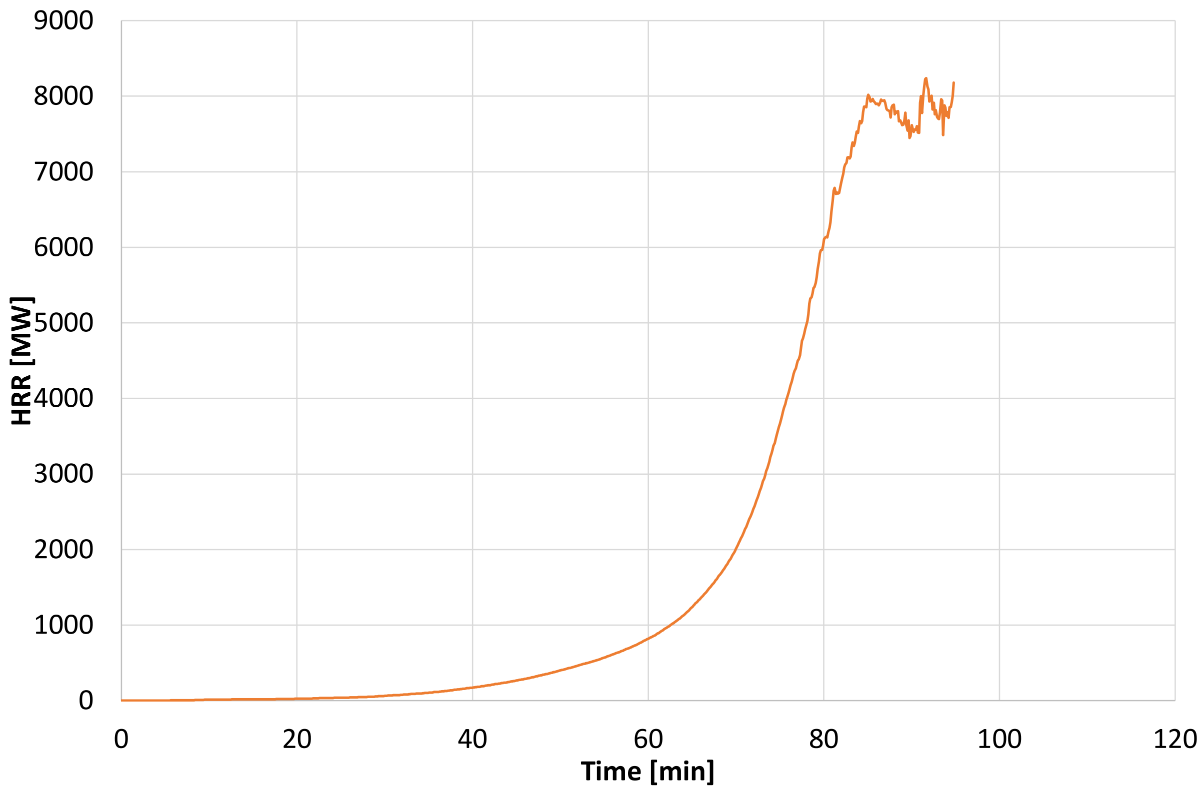
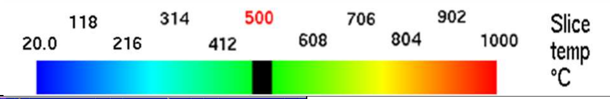
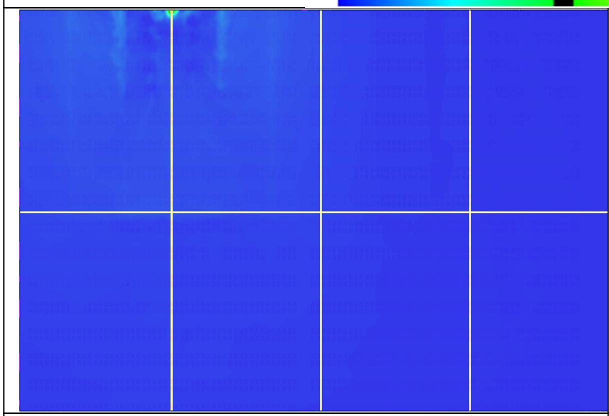
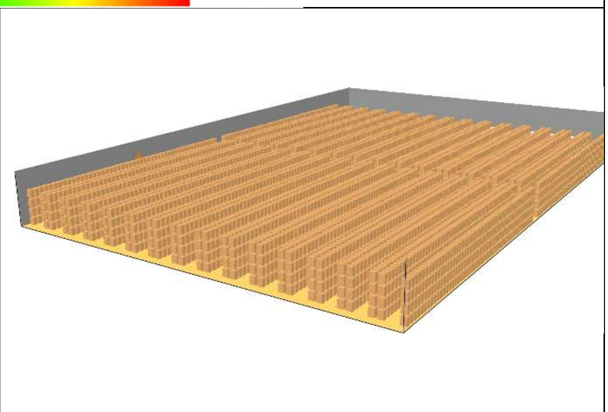


Figure 170: HRR calculated for the scenario W.4.1

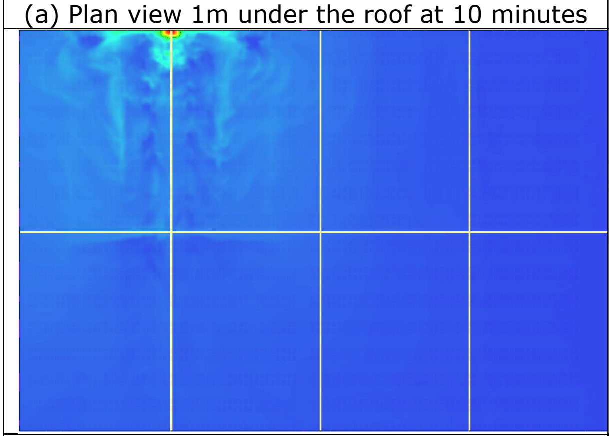




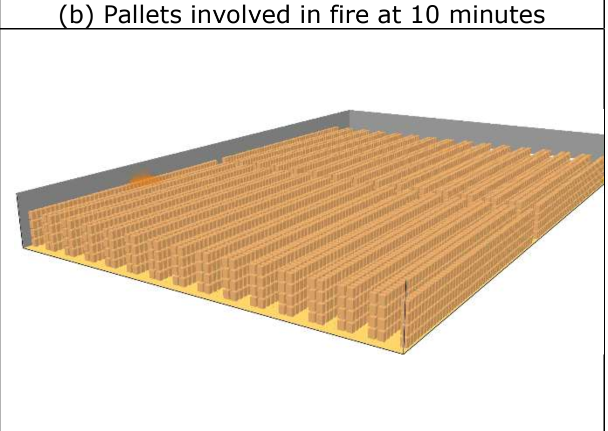
(a) Plan view 1m under the roof at 10 minutes



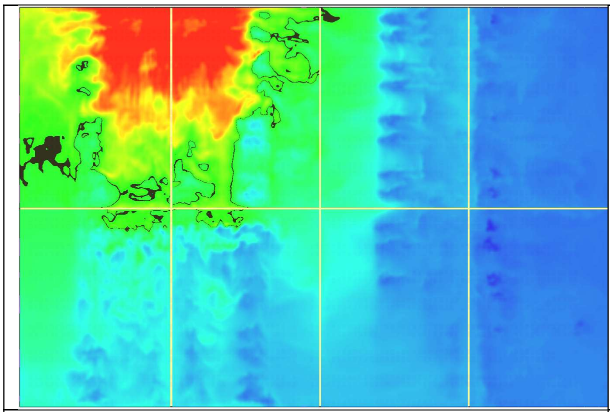
(b) Pallets involved in fire at 10 minutes



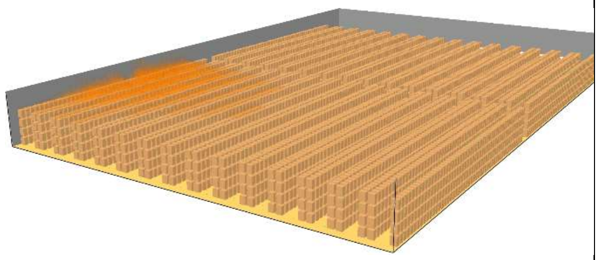
(c) Plan view 1m under the roof at 30 minutes



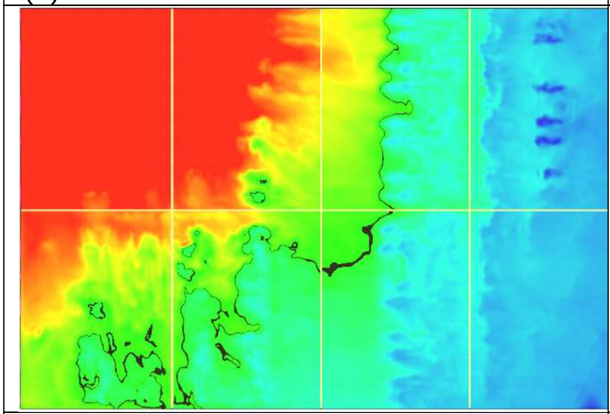
(d) Pallets involved in fire at 30 minutes



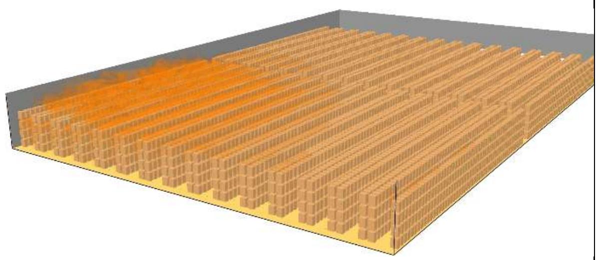
(e) Plan view 1m under the roof at 64 minutes



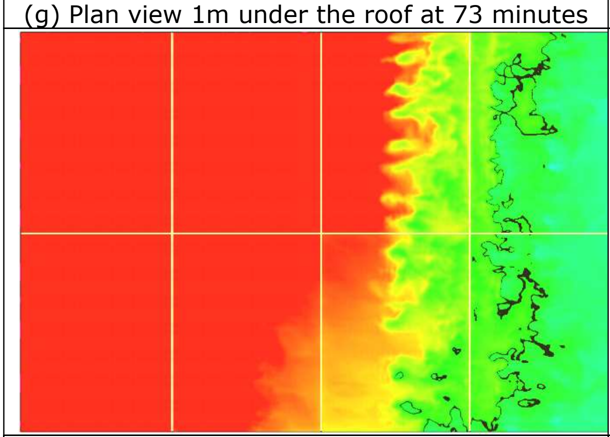
(f) Pallets involved in fire at 64 minutes



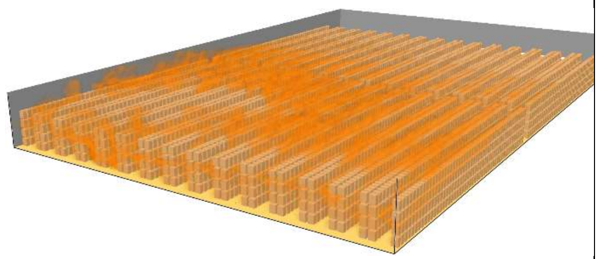
(g) Plan view 1m under the roof at 73 minutes



(h) Pallets involved in fire at 73 minutes



(i) Plan view 1m under the roof at 82 minutes



(j) Pallets involved in fire at 82 minutes

Figure 171: Temperature fields under the roof and surfaces involved in the fire

Figure 172 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 173). Thermocouple T1 shows a great increase in temperature after the starting of the combustion. At 11 minutes, the gas temperature reaches 600°C and 1000°C at 31 minutes. The increase at the other points is softer due to their distance from the ignition zone. However, all thermocouples show temperatures above 600°C at 48, 60, 67 and 72 minutes and 1000°C at 63, 71, 73 and 81 minutes for T2, T3, T4 and T5, respectively.

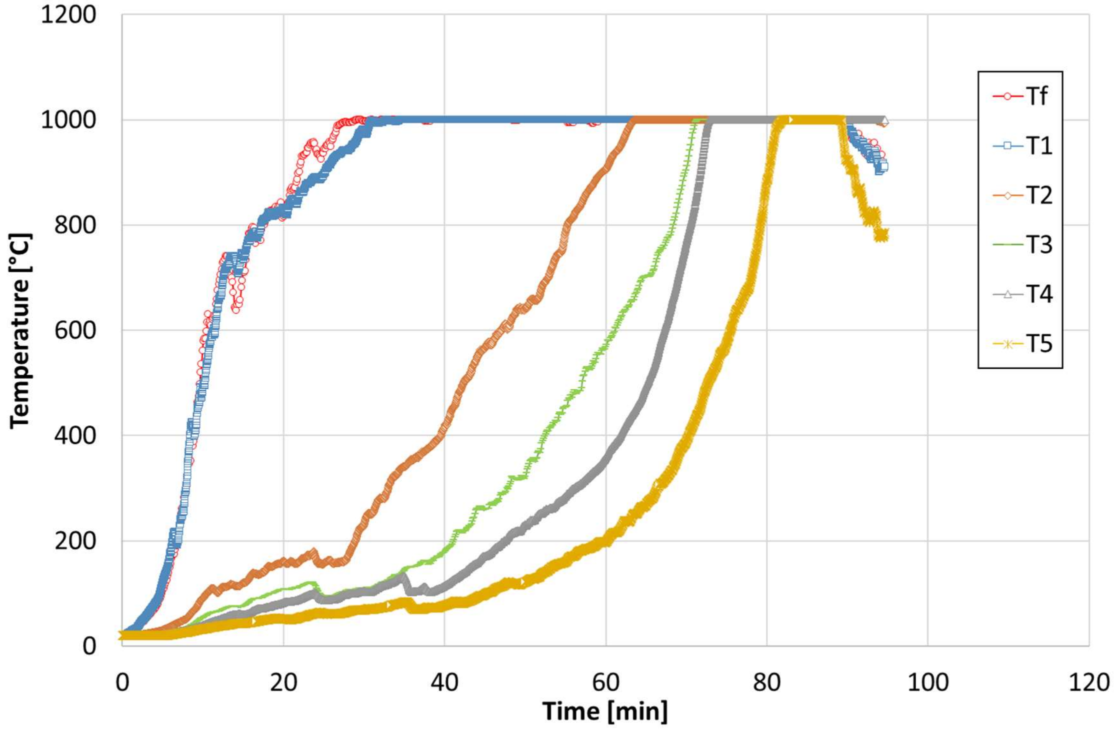


Figure 172: Gas temperature at different locations under the roof

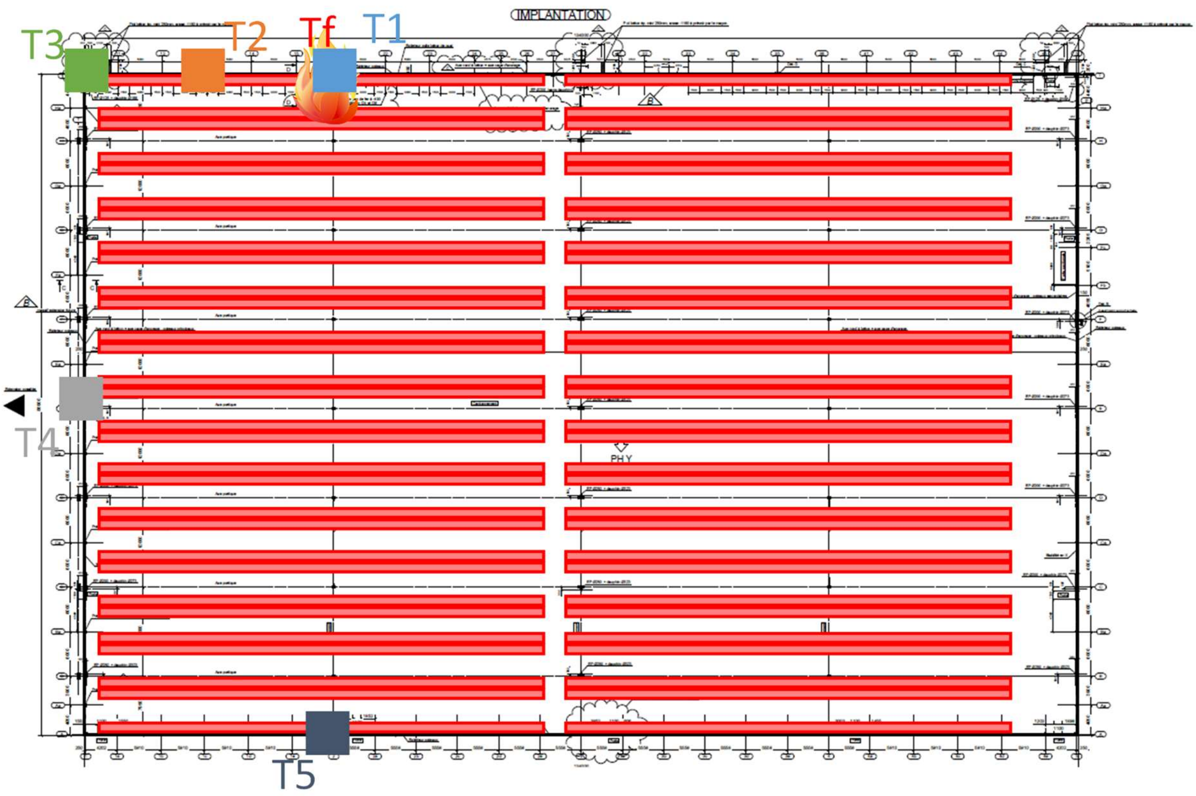


Figure 173: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple T1, are shown in Figure 174. It can be noted that temperatures reached along the height change during the whole time of the fire. Although the gas temperature rapidly increases above 5 m height to reach 600°C at 12 min and 100°C after 17 minutes, it increases a little more slowly at the lower parts, reaching 1000°C after 30 min.

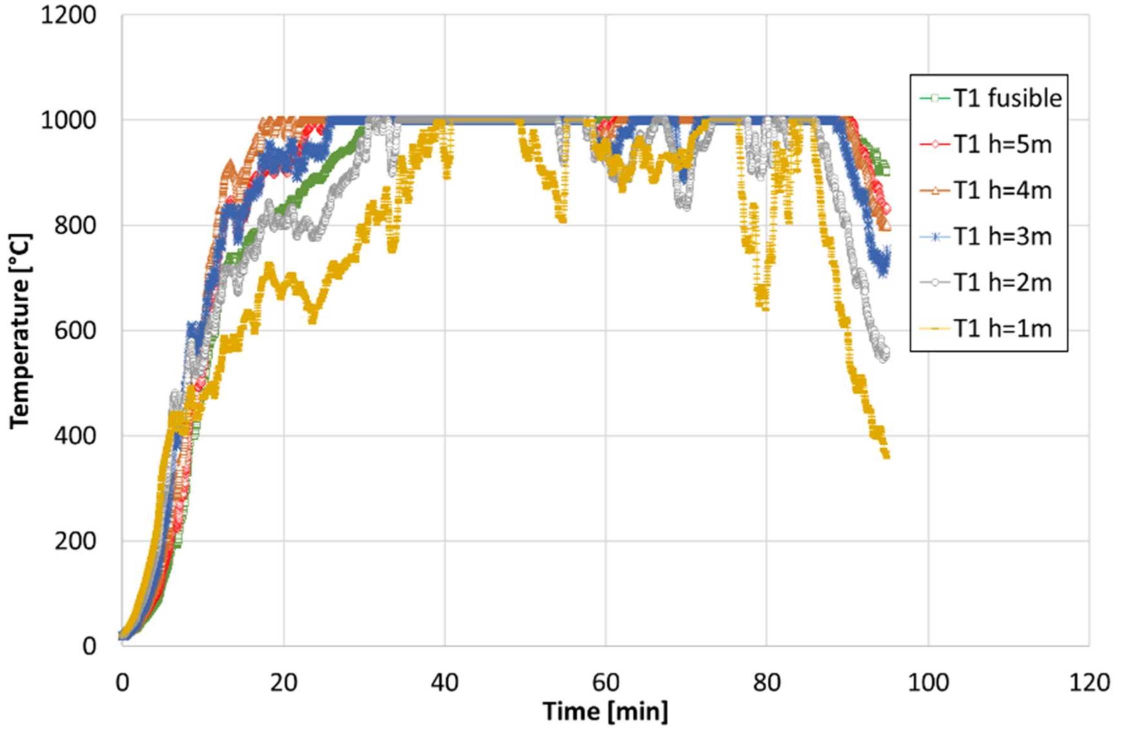


Figure 174: Gas temperatures versus time along the wall height at the location of thermocouple T1

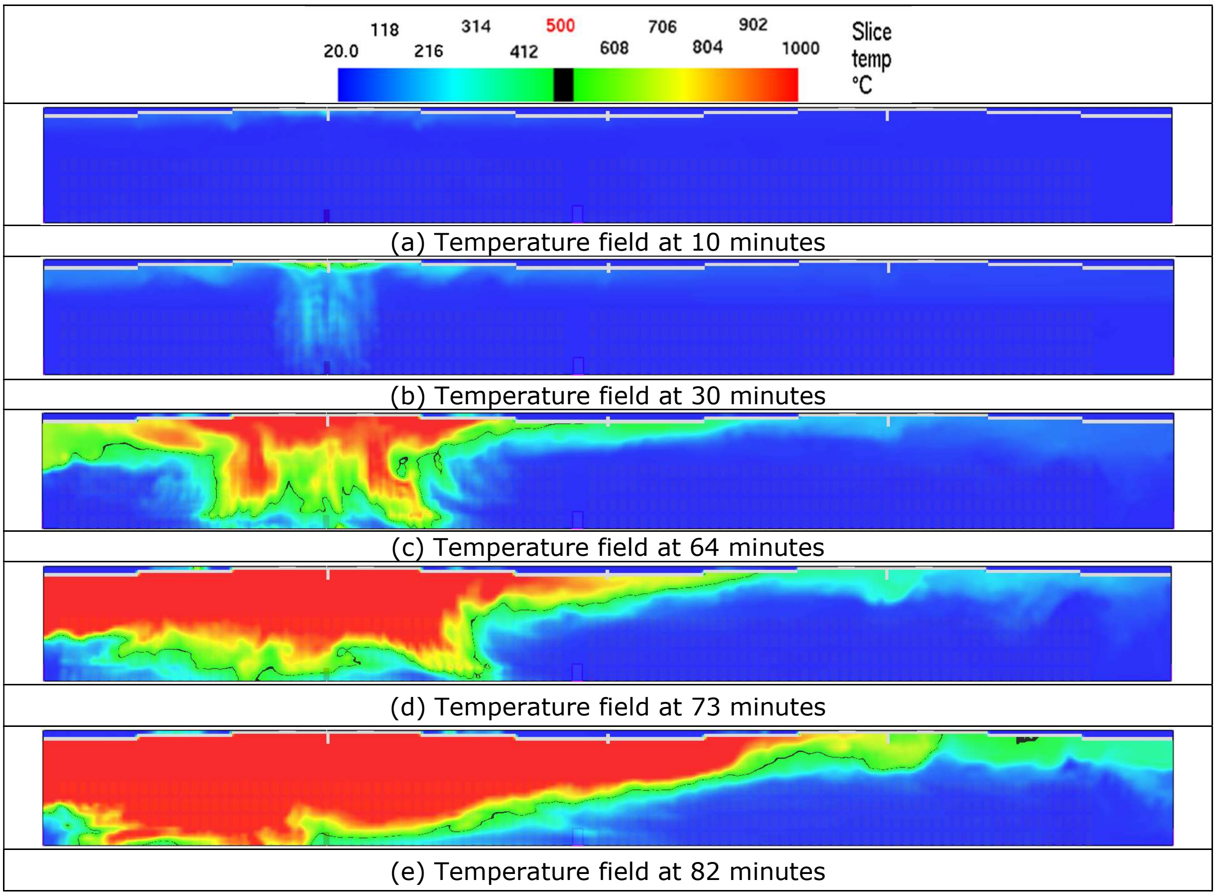


Figure 175: Temperature fields in the plan of the steel portal frame the nearest of the fire source position

A.20.Scenario W.4.2

This scenario concerns a 12000m² warehouse with a racking storage system. The source of fire is situated at the end of a central double row rack near one of the shorter building walls.

The calculated HRR is shown Figure 176. The plan views in Figure 177 show the temperature development at 1m below the roof at four different times. The perspective views show the spread of fire at the same times. The volume of the warehouse and its height delay the flashover until 48 minutes with the burning of the racks at the opposite side of the building (Figure 177h). After 69 minutes, a large part of the pallets of the warehouse is still not burning (Figure 177j). Although, gas temperature under the roof reaches 1000°C in all the left zone of the building.

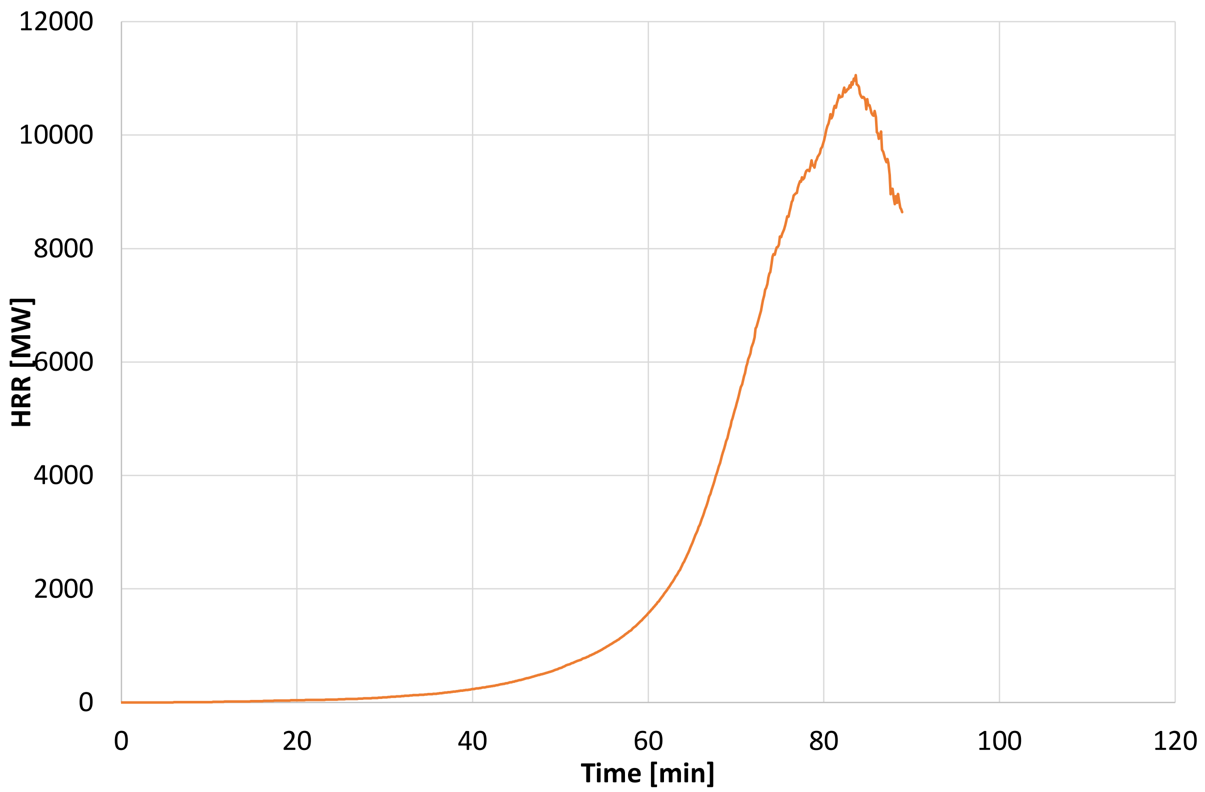
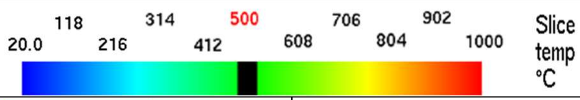
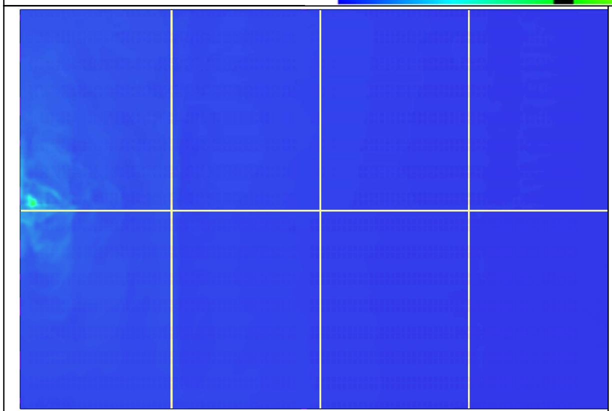
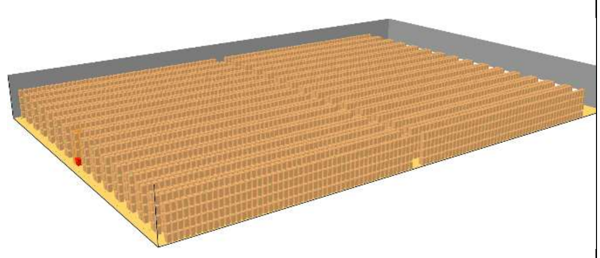


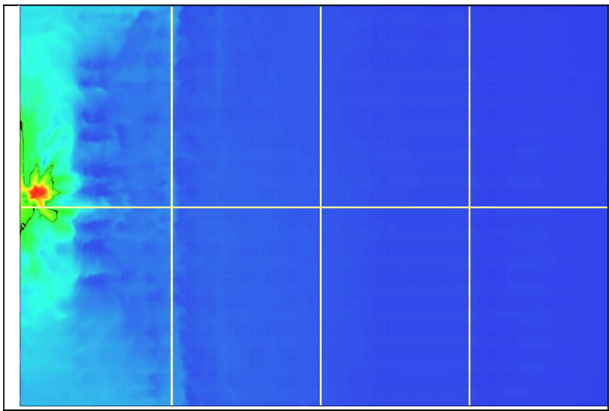
Figure 176: HRR calculated for the scenario W.4.2



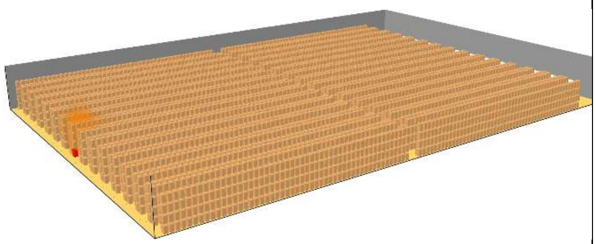




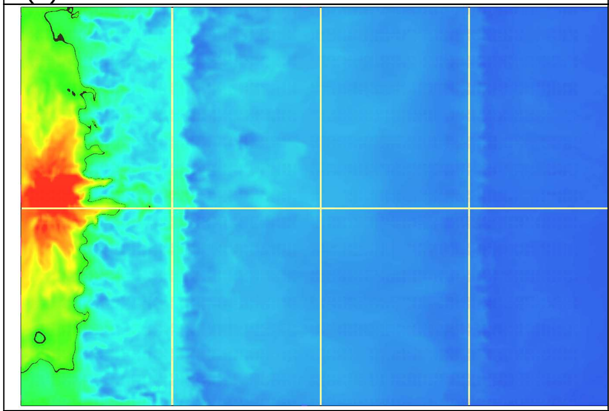
(a) Plan view 1m under the roof at 10 minutes	(b) Pallets involved in fire at 10 minutes



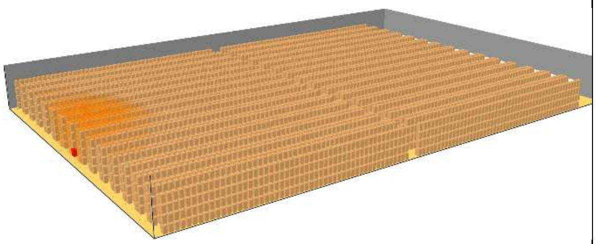
(c) Plan view 1m under the roof at 30 minutes



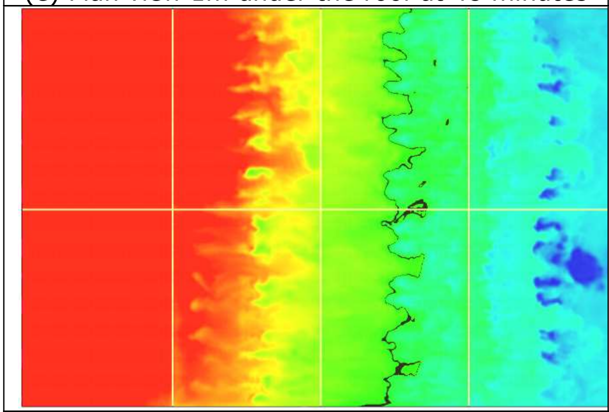
(d) Pallets involved in fire at 30 minutes



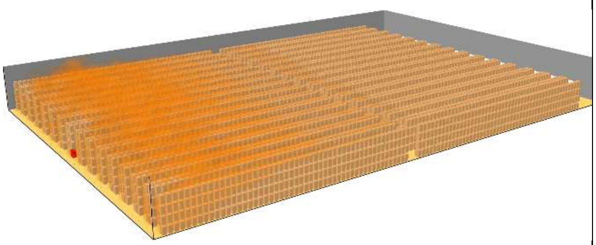
(e) Plan view 1m under the roof at 48 minutes



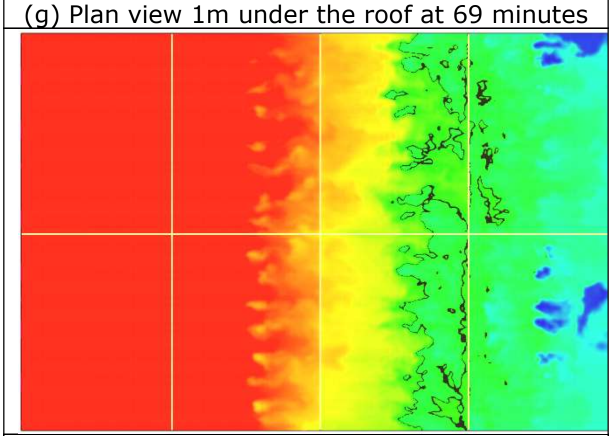
(f) Pallets involved in fire at 48 minutes



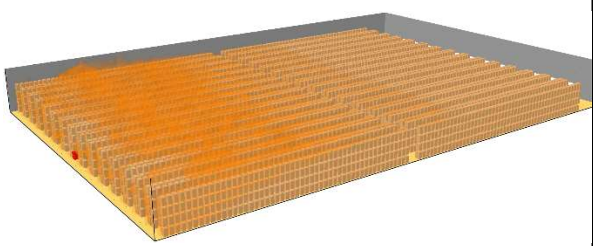
(g) Plan view 1m under the roof at 69 minutes



(h) Pallets involved in fire at 69 minutes



(i) Plan view 1m under the roof at 71 minutes



(j) Pallets involved in fire at 71 minutes

Figure 177: Temperature fields under the roof and surfaces involved in the fire

Figure 178 shows the gas temperatures calculated at 1m under the roof directly above the location of the fire source and at different locations along the building walls (where "fusible" systems connecting fire walls could be present), located close or far away from the fire source (as indicated in Figure 179). Thermocouple T4 shows a great increase of temperatures after the starting of the combustion. At 25 minutes, the gas temperature reaches 600°C and 1000°C at 50 minutes. The increase at the other thermocouples is softer due to their distance from the ignition zone. However, all the thermocouples show temperatures above 600°C at 52, 53 and 63 minutes and 1000°C at 64, 62 and 66 minutes for T3, T2 and T1, respectively. Thermocouple T5, at the opposite side of the warehouse, reaches 600°C at 80 minutes and 950°C at 88 minutes.

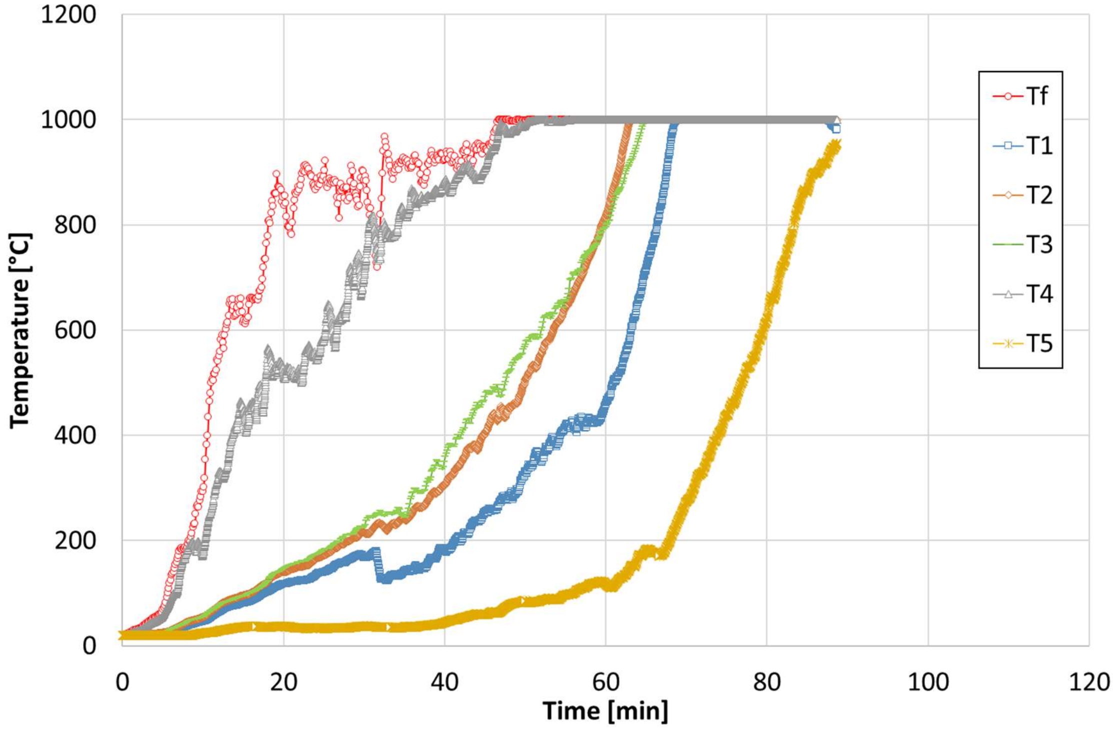


Figure 178: Gas temperature at different locations under the roof

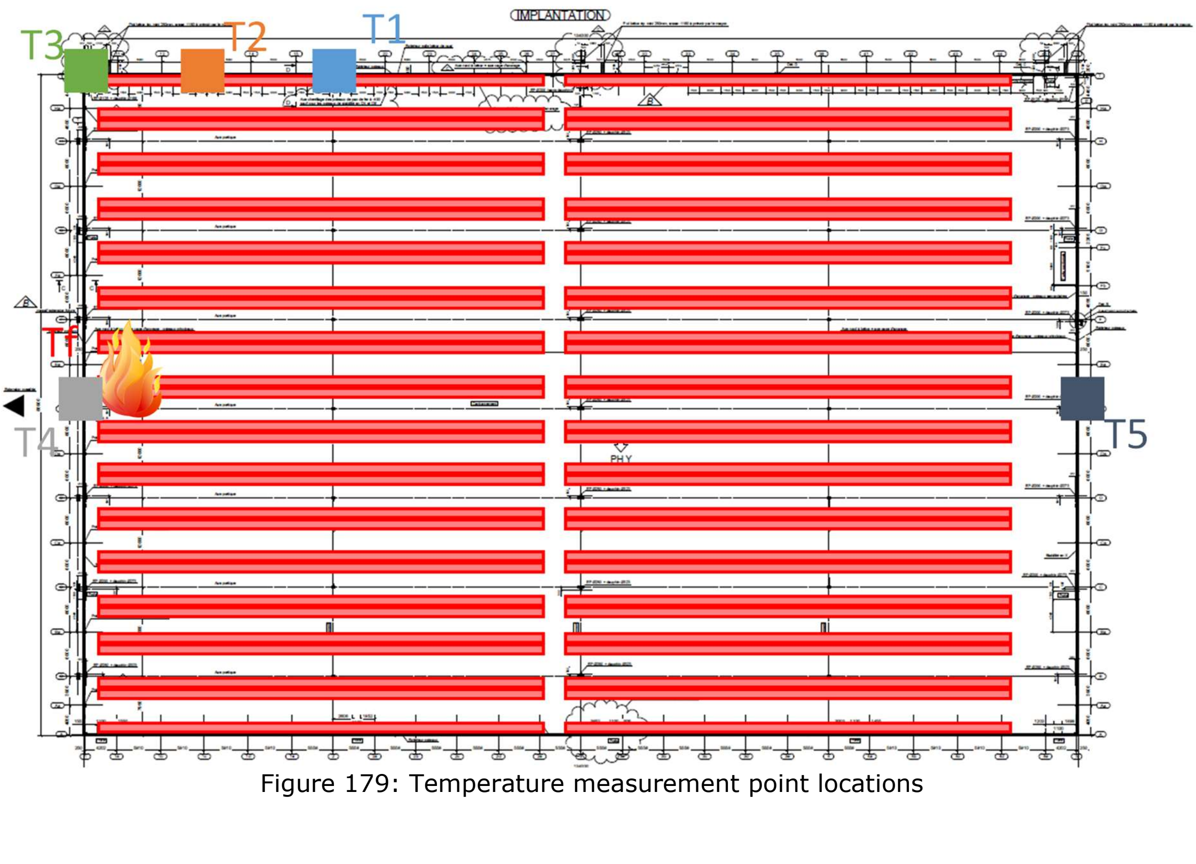


Figure 179: Temperature measurement point locations

Gas temperatures calculated at different heights along the wall nearest the fire source, at the same location as thermocouple T1, are shown Figure 180. The increase in temperature is softer under 4 m height. However, the temperature reaches 1000°C at 57, 60 and 70 minutes at 4, 3 and 2 meters height, respectively.

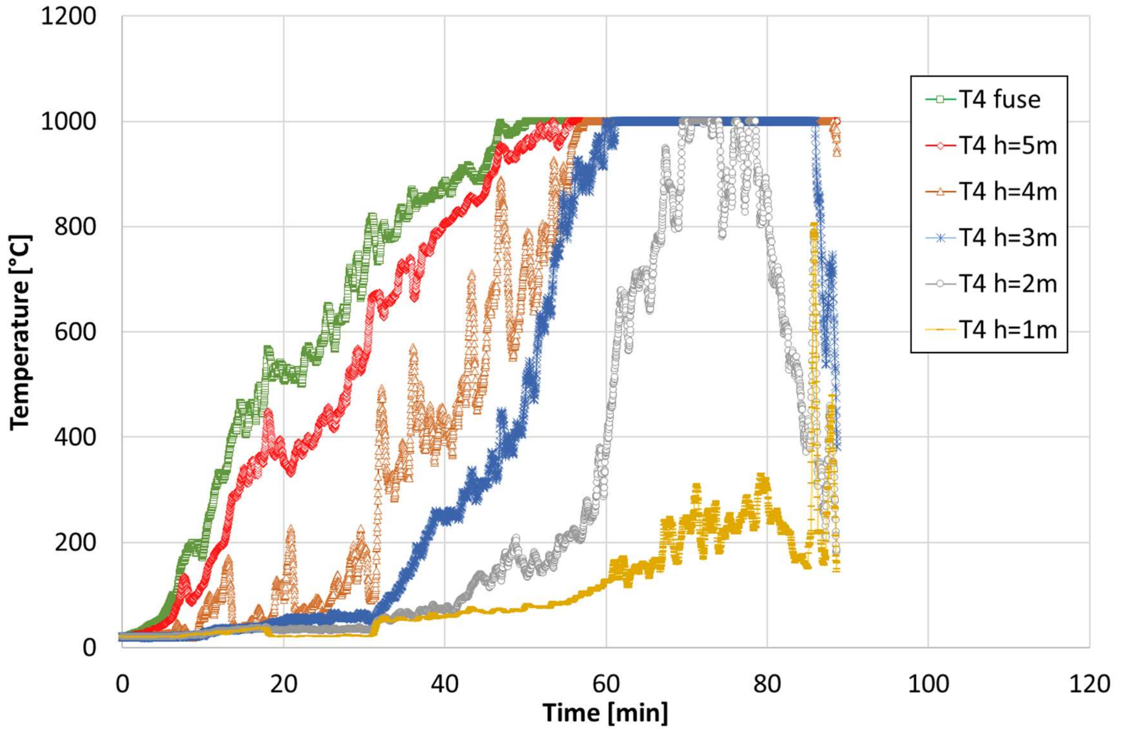
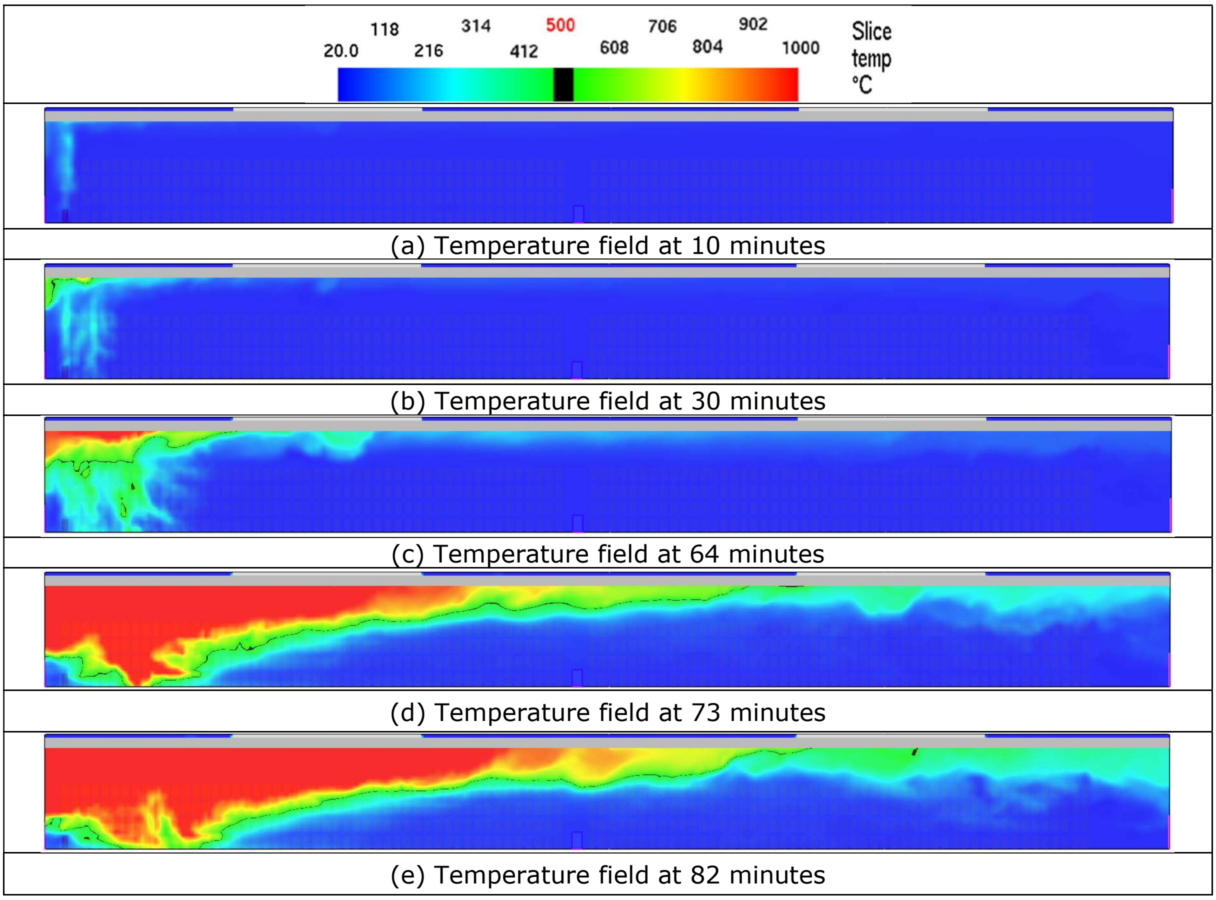


Figure 180: Gas temperatures versus time along the wall height at the location of thermocouple T4



(a) Temperature field at 10 minutes

(b) Temperature field at 30 minutes

(c) Temperature field at 64 minutes

(d) Temperature field at 73 minutes

(e) Temperature field at 82 minutes

Figure 181: Temperature fields in the plan of the steel portal frame the nearest of the fire source